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A STUDY OF THE RHEOLOGICAL PROPERTIES OF THICKENED FLAME THROWER FUELS.

N.G. MAXWELL TUCK

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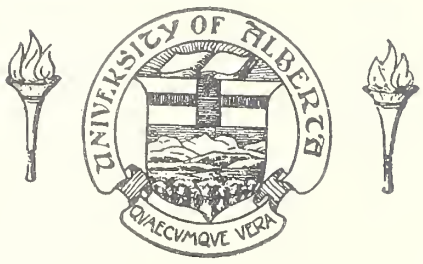

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A STUDY OF THE RHEOLOGICAL PROPERTIES OF THICKENED FLAME THROWER FUELS

Submitted in Partial Fulfillment

of the

Requirements for the Degree of

MASTER OF SCIENCE.

---

by

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Under the direction

of

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A STUDY OF THE RHEOLOGICAL PROPERTIES OF THICKENED FLAME THROWER FUELS

GENERAL INTRODUCTION

As is well known, the flame thrower has been used widely during the present war as a combat weapon. The investigation reported in that which follows deals with flame thrower fuels, of the hydrocarbon-soap gel type, and has been directed to the objective of developing laboratory tests that can evaluate the field performance of the fuel. The original objectives included a field test suitable for evaluation of performance and applicable to mixes made in combat areas. Inasmuch as gel type fuels are not generally made except in central plants, the restriction imposed by field conditions does not necessarily apply.

There are several different purposes for which a flame thrower may be used. First, there is the demoralizing effect; secondly, their casualty producing power when projecting an ignited jet into pillboxes and bunkers; thirdly, their ability to ignite combustibles at some short distance away. To date, no single fuel has been prepared that will serve all these purposes. The desirable features of a flame thrower fuel in general are as follows:

1. High calorific value.
2. Ready ignitability.

3. Adhesiveness--so that burning takes place on the target.
4. Resistance to disintegration in flight.
5. Stability in storage.
6. Ease of production from materials available in combat areas.

The fuel that was first used was gasoline or fuel oil. This produces an intensely hot flame that breaks up quickly in flight, so that its range is extremely limited. Its main purpose is for its psychological effect, and is still widely used.

In an effort to obtain increased range, aluminum soap-gasoline gels have been developed. These are of two types: the British type, known as the F.R.A.S., and the United States type, known as Napalm. These fuels, commonly referred to as thickened fuels, are thixotropic gels and behave as non-Newtonian fluids. Such fuels can be projected in the form of a stable rod-like jet giving a large increase over fluid fuels in effective range, stick to the target, and can be projected through small openings into bunkers and pillboxes. These fuels are inferior to fuel oil on the basis of pourability, penetration of vegetation, concealing the flame thrower operator, and also in psychological effect. Furthermore, with fuels containing a high concentration of thickening agent, and particularly in flame throwers that operate at high pressures, considerable difficulty has been experienced in obtaining good ignition.

A single fuel has been sought that will combine the virtues of each type of fuel; that is, easy pourability, maximum range, maximum intensity of burning, etc. One field in which considerable investigation is being carried out at the present time is that of peptized gels. Ideally, such fuels would be of low viscosity when disturbed, but recover gel-like properties when at rest. The peptizers that have been investigated most thoroughly are:

1. Xylenol - this permits gels to be prepared at low temperatures, and is widely used in F.R.A.S. fuels.
2. Alcohol - this gives more stable gels than the other peptizers. Gels peptized with alcohol-xylenol mixtures are particularly suitable for tropical use because of their low sensitivity to temperature changes.
3. Water - this has been used mainly because of its availability in the field. Although the gels prepared with water are comparable with those from other peptizers in some respects, it is definitely inferior in others.

In the final analysis, the evaluation of any fuel can be made only by actual field performance. This is not only time consuming but is costly as well. Consequently, it is desirable to predict performance of a given fuel from measurements of certain of its physical properties in the laboratory. Empirical relationships have been found between

certain physical properties and the mean effective range that are applicable to fuels of one type; for example, sufficient data has been obtained so that the performance in a particular flame thrower of a straight Napalm gel can be predicted from its Gardner consistency, or from "healing time" measurements. This relationship, while doubtless general, has not yet been developed to a point of correlating different fuels and different flame throwers.

LITERATURE REVIEW

Although colloidal systems have been known as such and studied for nearly a century, the main interest has been centered around systems in which water is used as the dispersion medium. Only very recently has there been any intensive study of volatile hydrocarbons as dispersion media. Since the application of these systems is for use as flame thrower fuels, much of the literature is confidential and originates through the Directorate of Chemical Warfare and Smoke, Ottawa.

Graham laid the foundations for colloid chemistry and was responsible for much of the terminology still in use. The literature is very extensive and this review will be a very brief extract of that on thixotropy and mechanical behavior. Freundlich (10, 12, 11) carried out extensive studies on colloids and it was due largely to his work that this subject was established on a firm scientific basis. He investigated the phenomenon of thixotropy which is gel liquefaction by means of mechanical disturbance with the subsequent gelation after a period of quiescence. He also presents a discussion on the relation of viscosity with the rate of shear.

Bogue (3), Hartman (17), Hedges (19), Rideal (47), and Ware (50) discuss several of the theories on gel structure that have been advanced. The vast majority of

investigators incline to the view that gels are two phase solid-liquid systems. There is still considerable difference of opinion as to the exact nature of the solid framework and the exact manner in which the liquid is entrained. It is quite possible that the internal phase differs in different gels; in some it may be in the form of thread-like crystals, in others as solvated particles, etc. Von Buzagh (48) gives a detailed account of the forces acting in colloid formation and refers particularly to the role played by dipole moments and other Van der Waal's forces in gel structure. Kruyt (21) presents a discussion on gelatinization, and illustrates the influence of the two stabilizing factors, solvation and charge, in this process.

Peptization refers to the liquefaction of gels by the addition of a small quantity of another substance. All the known peptizers for aluminum soaps in gasoline contain polar groups in the molecule. In a study of the three dinitrobenzenes (39) it is revealed that the efficacy of these as peptizers is in no way related to the dipole moment of the molecule as a whole. The pure isomeric xylenols (34) are found to differ widely in their peptizing effect; their effectiveness is related to the closeness of the methyl group.

Gemant (14), in dealing with colloid systems, discusses "structural viscosity" and the phenomenon of decreasing viscosity with increasing rate of shear for these systems. F.R.A.S. fuels (43) have a constant viscosity for

rates of shear less than 0.1 to 0.2 sec^{-1}, and undergo a marked decrease in viscosity for rates of shear of more than 1.0 sec^{-1}. The "initial viscosity", that is, viscosity at very low rates of shear, is a criterion for the range of unignited jets of F.R.A.S. fuels. For Napalm fuels (8, 23), at rates of shear greater than 100 sec^{-1}, the log of the viscosity is a straight line function of the log of the rate of shear.

Knudsen and Sereda (20), in studies of the capillary viscometer, noted an enlargement of the jet that reached a maximum in cross section some short distance from the capillary exit. This was assumed to be a manifestation of thixotropy. The gel structure is ruptured in the capillary where the shearing stress is high and reforms once the gel passes into the air where the shearing stress is extremely low. Thus, the time for a particle to reach this section of maximum enlargement would be the "healing time" or "relaxation time" of the gel. The healing time was found to be a direct function of the velocity of the jet and the diameter of the capillary. Healing time, under definite experimental conditions, is characteristic of the gel. A graphical correlation has been established for the prediction of the performance of Napalm fuels in a model flame thrower and healing time measurements.

The mean effective range and rod length (8) can also be predicted for Napalm fuels from the ball drop viscosities (initial viscosity) and Gardner Mobilometer data.

THEORY

Thomas Graham, in a series of papers published between 1849 and 1869, laid the foundations upon which colloid chemistry now rests. He distinguished between two classes of compounds: those that readily diffuse through an aqueous medium--crystalloids, and those that did not--colloids. He attributed the difference between these two classes to the state of subdivision of the particles. It is now common practice to divide colloids into two broad systems, the lyophobic and the lyophilic. Glasstone (15) lists the following as being characteristic of lyophilic colloids:

1. Surface tension is often lower than that of the dispersion medium.
2. Viscosity is much higher than that of the medium.
3. Small quantities of electrolytes have little effect, but large amounts may cause salting out.
4. The particles cannot be readily detected in the ultra microscope.
5. The particles may migrate in either direction or not at all in an electric field.

Gel Structure

There is no sharp line of demarcation between a lyophilic sol and a gel. In some systems, a change in the concentration of the disperse phase, a change in the temperature, or a change in the concentration of electrolytes will

serve to transform one to the other. Furthermore, the transformation from gel to sol may be brought about by mechanical agitation.

Ostwald defines a gel as a colloidal semi-solid system rich in liquid. There is no general agreement as to the precise nature of the structure of a gel. A large number of theories have been advanced, none of which have been generally accepted. The vast majority of investigators incline to the view that gels are two phase solid-liquid systems in which there is a network or cellular arrangement of solid phase permeated by liquid. There is still considerable difference of opinion as to the exact nature of the solid framework which is assumed to entrain the liquid phase and the manner in which this framework is formed. The theories of gel structure are discussed by Bogue (3), Hartman (17), Hauser (18), Hedges (19), Kruyt (21), Rideal (47), Von Buzagh (48), Ware (50), and others. A few of these, having found most widespread acceptance, may be summarized:

1. The distensible body is porous, and swelling results from solvent penetrating the pores and being held by capillarity or by molecular attraction.
2. The distensible body is made up of small anisotropic crystal-like molecular aggregates which retain their identity, even when the substance goes into colloidal solution. The micelles take up water in such a manner that they are surrounded by a solvent layer, the thickness of which is de-

termined by the relative intensity of the attraction of the micelles for the dispersing medium and for eath other.

3. The internal phase is a solid skeleton making up a network of walls and forming irregular cell-like structures, the voids of which contain the external phase.

4. Pluri-molecular units, the smallest of which are the micelles, are built up by the orientation of definite atomic groups entirely by the sense of the theory of molecular orientation due to structure.

Gels are formed from those compounds, one part of whose molecule is soluble in the dispersing medium and one portion insoluble, that is, the molecule must contain a lyophobic as well as a lyophilic group. If the molecule is completely insoluble, as is the case with metals in water, we may have the formation of a lyophobic sol; if the complete molecule is soluble, a solution is formed. The first action is thus doubtless one of solvation.

The chief factor for intermolecular forces is the distribution of electric charge. In polar compounds the centres of electrical charges do not coincide; and even such systems, the algebraic sum of whose electrical charges is zero, emit electrical forces. Two dipoles approaching each other will take up such relative positions as to involve the greatest diminution of energy. Thus, in non-coherent mole-

cular disperse systems, molecular attraction causes orientation of the dipoles and thus the formation of "loose swarms". If these molecular forces possess sufficient intensity, stable dynamically and sterically self-contained molecular complexes may be formed as is the case in the formation of association molecules. However, molecular attraction due to permanent dipoles is not the only attraction leading to the aggregation of molecules. If the molecule contains movable instead of fixed charges, they become polarized on approaching each other. If the molecules happen to come into position so that they repel each other, the charges will become displaced, and consequently the dipole moment diminishes, at the same time the repelling force diminishes and this means a diminution in the free energy. A particularly characteristic property of the forces which appear through reciprocal polarisation with movable dipoles consists in their being independent of temperature, and, therefore, primarily dependent only on the internal construction of the molecules. This reciprocal polarisation supplies that part of Van der Waal's cohesive forces which is independent of temperature. Moreover, electrons in the atom may suffer disturbances if the molecules approach each other sufficiently closely. This results in wave mechanical attracting forces that are effective at greater distances than molecular dimensions, independent of the position of the molecule and of the temperature, and that are superimposable.

Gel formation thus consists of

1. Solvation of the molecules.
2. Attraction between molecules by Van der Waal's forces to yield a semi-rigid structure.

Viscosity

As ordinarily encountered, the liquid state of matter is considered to have a constant viscosity regardless of the shearing stress, that is, the tangential force per unit area, applied to it. Plotting the rate of flow against the applied stress yields a straight line of constant slope passing through the origin as illustrated in Figure (1-I). Liquids exhibiting such a property are termed Newtonian liquids. It might be that in Newtonian liquids the divergence from linearity occurs at high stresses that are not usually met in practical cases. The reason for believing in such a general non-linearity is, however, more theoretical than experimental.

Certain liquids have been encountered which show departure from the classical or Newtonian behavior. In this case, the rate of shear increases more than proportionally with the stress, that is, the viscosity decreases with increasing stress. Figure (1-II). Gemant (14) gives an account of the properties of non-Newtonian liquids.

The occurrence of non-Newtonian liquids is confined almost exclusively to colloidal systems. It is probable that all disperse systems, such as suspensions,

Figure 1

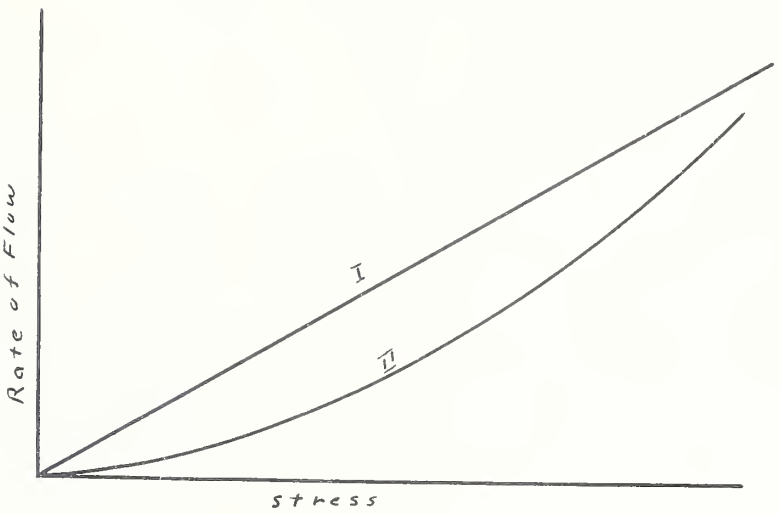
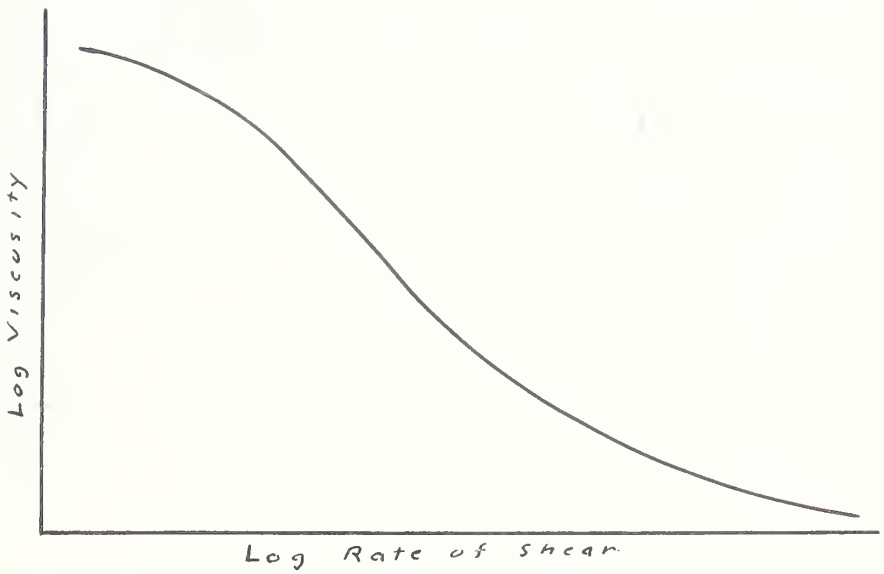


Figure 2



emulsions, sols, etc., show this property, but the effect may be negligible if the particle concentration is low. However, when the concentration is increased as in the case of gels, the effect becomes more pronounced. The particles become sufficiently numerous or large, or both, so that they exert a considerable influence on each other. It is thus related to structure and is termed "structural viscosity".

A number of standard laboratory tests have been developed in an effort to correlate viscosity and flame thrower fuel performance. The most important of these methods are

1. Ball drop viscosimeter.
2. Capillary viscosimeter.
3. Gardner Mobilometer.

A large number of others have been suggested (7, 27).

1. The Ball Drop Viscosimeter

This type of instrument has been checked with the Couette viscosimeter using F.R.A.S. fuels and the initial viscosity by these two methods found to agree within ±5%, as long as the ratio, velocity:diameter of ball, does not exceed 0.2 (43, 44). This property is characteristic of the gel. To obtain good results it is not necessary to centre the ball accurately nor to eliminate parallax. The initial viscosity has been found to govern the extreme range of unignited jets of fuels of the F.R.A.S. type.

With Napalm fuels, the results do not seem to be so consistent. Variations as high as 30% have been

noted in initial viscosity determinations by this method (7).

2. Capillary Viscosimeter

Brown and Cousins (38) report that for Napalm fuels the viscosity at any rate of shear as determined by the capillary viscosimeter is always higher than that at the same rate of shear when determined from flow in pipes. Garner, Nessan and Wood (46), working with F.R.A.S. fuels, discovered that the resistance to flow in pipes is affected by both the diameter and the length to diameter ratio. These effects are not due to kinetic energy corrections, nor to elastic deformation at entrance. For all diameter tubes, as the length:diameter ratio is increased, the viscosity at a given rate of shear decreases, reaching a constant value when the ratio exceeds 50. This ratio has been determined by others to be between 40 and 80 (9).

This method has been used widely for determining the viscosity at all rates of shear, excepting very low ones. Thus it is complimentary to the ball drop method. Combining the two methods yields a curve as shown in Figure 2. For Napalm fuels, over limited ranges at high rates of shear, plotting the log of the viscosity against the log of the rate of shear yields an approximate straight line, as shown in Figure 3.

3. Gardner Mobilometer

The interpretation of Gardner Mobilometer data is still very uncertain. The 100 second load (Gardner consistency) is believed to be characteristic of the viscosity

at low rates of shear; low values (50 grams or less) indicate flash burning. The 1/10 second load is characteristic of the viscosity at high rates of shear; a high value (2000 grams and higher) indicates a long unbroken rod. A high slope indicates breakdown.

In one sample, the Gardner consistency can be duplicated within plus or minus 10 grams. The consistency of mixes of the same concentration can be reproduced within plus or minus 10%.

Thixotropy

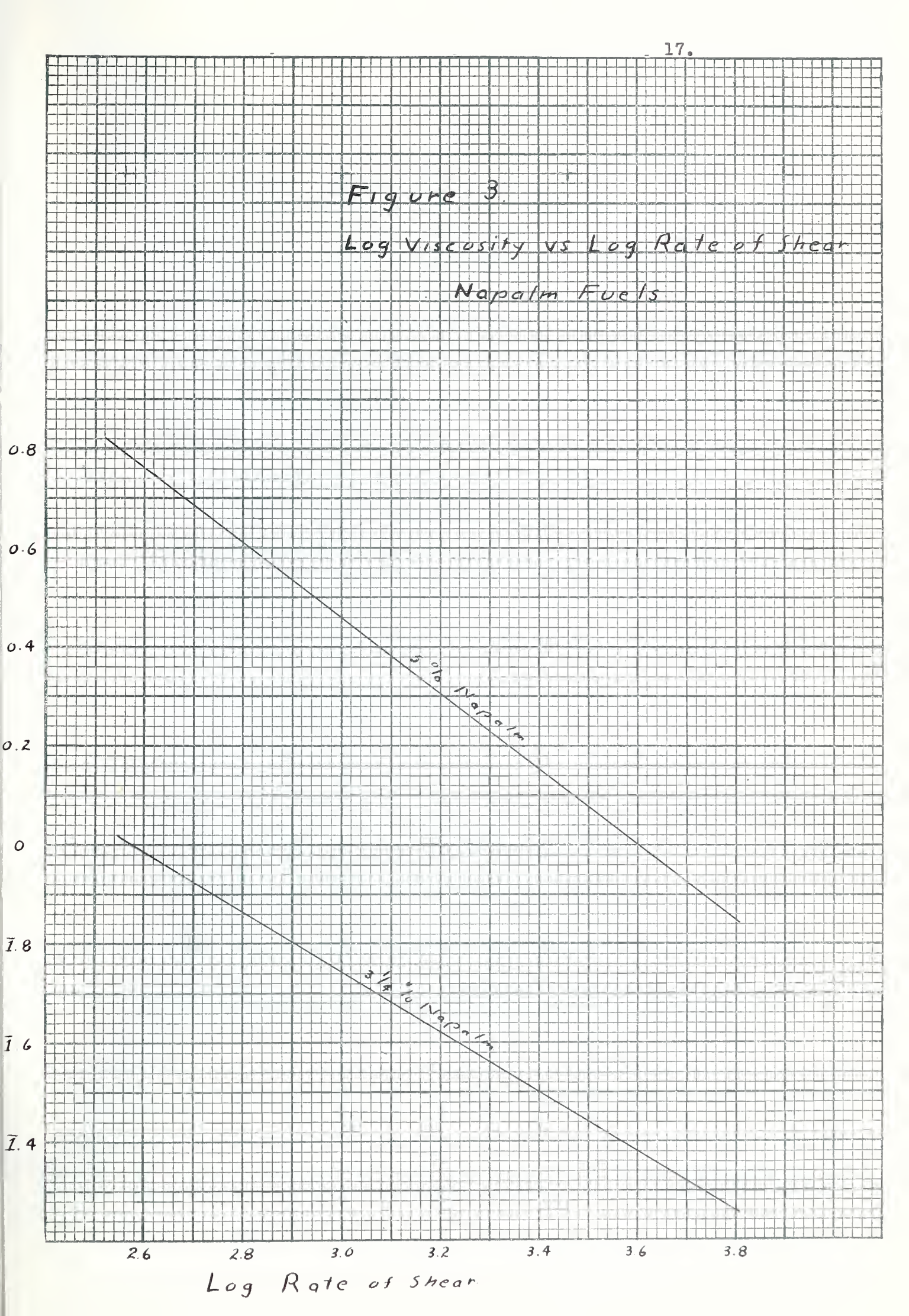
Thixotropy is a peculiar "unsetting" of a gel and may result from any means which produces internal stress. This phenomenon is discussed by Freundlich (12, 11), Von Buzagh (48), Alexander (1), Kruyt (21), and others. When a gel is subjected to a sufficiently great mechanical deformation, it liquifies to form a sol, but after a period of quiescence it again assumes its original semi-solid condition. This phenomenon suggests that the properties of a gel are dependent on the preservation of a particular structure and that this structure is destroyed by agitation.

Two main theories have been proposed to account for thixotropy. According to the "Solvation Theory", the colloidal particles are surrounded by lyospheres, or thick envelopes of oriented solvent particles, and that these eventually become so large that freedom of motion is lost. Mechanical agitation ruptures these lyospheres and liquefac-

Figure 3.

Log Viscosity vs Log Rate of Shear

Napalm Fuels

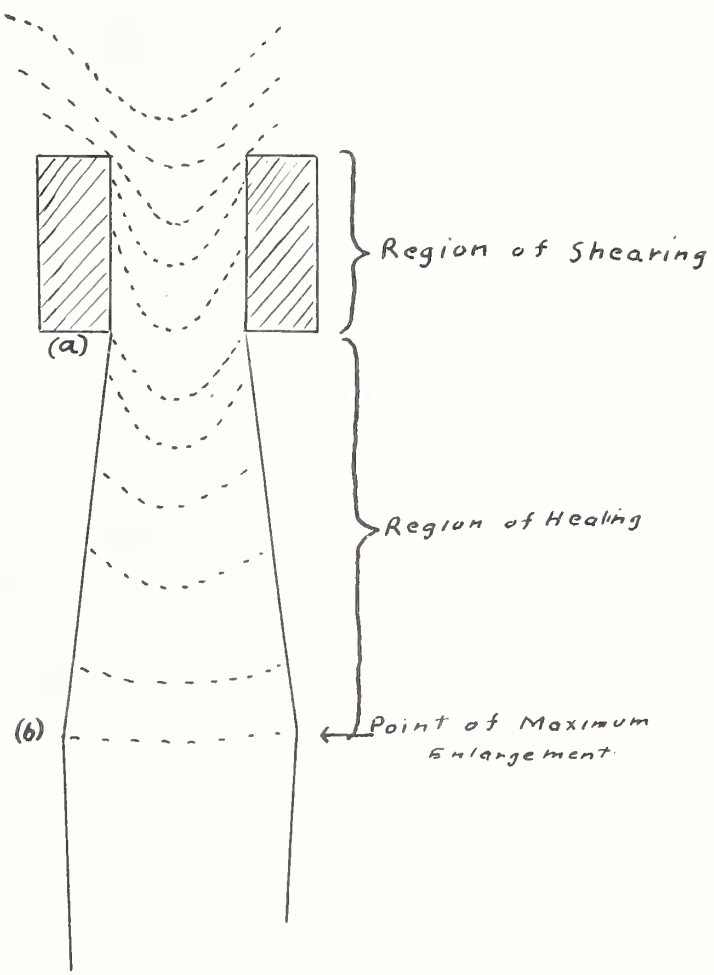


tion results. According to the "Oriented Coagulation Theory", thixotropic gels are formed only if the particles are anisotropic so that the electric charge and the solvated layers are unequally distributed. The particles tend to coalesce, but owing to their shape can form a stable gel only if orientated correctly. Any mechanical stress will tend to reduce the surface of contact and hence destroy the gel structure. It is probable that liquefaction occurs because of a rupture of the intermicellar forces and a tearing apart of the fused solvated shells between the micelles.

The setting time or "healing time" of thixotropic gels is characteristic of the systems if the experimental conditions are maintained constant. The solidification proceeds at a definite rate, for both the rearranging of the building units of the solvated shells, as well as the new association of the particles, require a definite time. Thixotropy is an isothermal change, it being possible for the system to be either "solid" or "liquid" at the same temperature without altering its volume.

In dealing with the pressure viscosimeter, it was noted (20) that at certain pressures the jet gradually increased in cross section and reached a maximum a short distance from the capillary, after which the jet tapered with decreasing diameter. In the capillary the gel is subjected to high shearing stress, so that the gel network is ruptured. The velocity distribution ought to be parabolic or approaching it, as would be the case with a newtonian liquid undergoing streamline flow.

Figure 4


Region of Shearing
(a)
Region of Healing
(b)
Point of Maximum Enlargement

The dotted radial lines (Figure 4) indicate the velocity gradient through the cross section of the ejected fuel. On leaving the capillary at (a), the velocity gradient should decrease which would result in a gradual piling up of the gel. From the point (b) it is believed that the gel flows in a solid rod. The time for a particle to flow from (a) to (b) is believed to be the healing time or relaxation time of the gel under the experimental conditions.

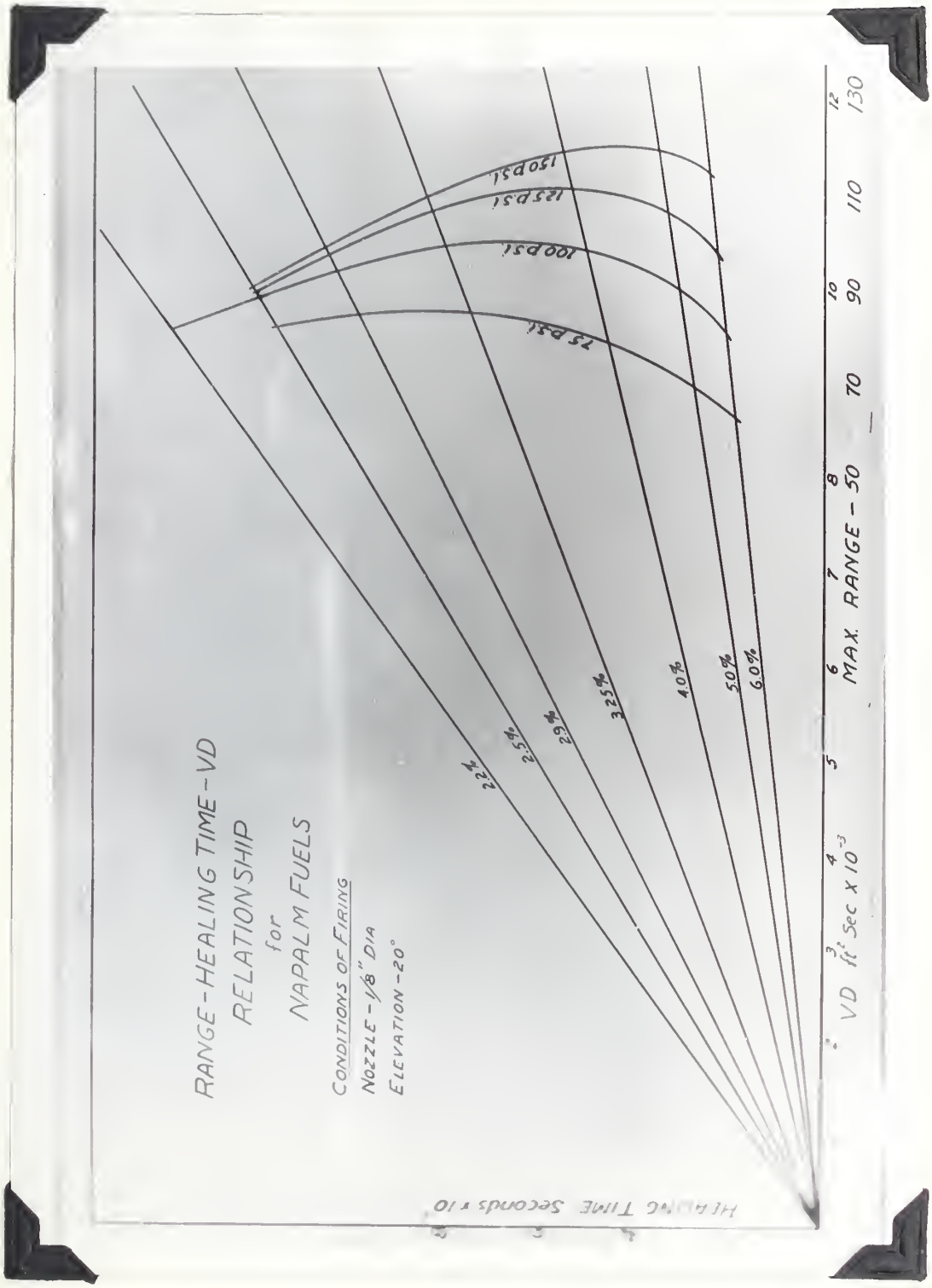
If the healing time is plotted against the factor, V.D., a straight line of constant slope, passing through the origin, results. Ageing increases the healing time; an increase in temperature also increases the healing time.

A relationship has been established by which it is possible to predict the range of fuels thickened with Napalm by a measurement of the healing time. This is represented graphically in Figure 5. This is for an experimental flame thrower operating under specific conditions, but it should be capable of interpretation in terms of combat flame throwers. In confirmation of this it is reported (6) that "the percentage of Napalm in gasoline which gives the maximum range with suitable target effect.....is 4-1/2%". Others (24) report that little increase in range is attained by increasing the concentration above 4%.

Peptizers

The term peptization denotes the liquefaction of a gel by the addition of a small quantity of another substance. Rather extensive studies have been carried out on

FIGURE 5


RANGE-HEALING TIME-VD
RELATIONSHIP
for
NAPALM FUELS
CONDITIONS OF FIRING
NOZZLE-1/8" DIA
ELEVATION-20°
HEALING TIME Seconds x 10
VD ft³ Sec X 10⁻³
MAX RANGE - 50
150 PSI
125 PSI
100 PSI
75 PSI
2.2%
2.5%
2.9%
3.25%
4.0%
5.0%
6.0%

the peptization of gels in water systems by electrolytes; this obviously is not applicable to hydrocarbon systems. Peptization consists of loosening the bonds between adjacent particles by substituting solvent or peptizer to satisfy the broken linkages.

It is now generally assumed that a peptizer must be appreciably soluble, either directly or indirectly in the liquid medium. Moreover, it must have some affinity for the colloidal material; for example, it may be strongly adsorbed on the surface of the colloidal particles, freeing them from each other and exposing soluble groups to the solvent. Since the intermicellar forces responsible for the semi-rigid structure of gels consists largely of the electrical forces arising from dipole moments, it seems logical to assume that only polar compounds, or those compounds containing polar groups, should behave as peptizers. These may also act to break down the molecular aggregates, or micelles, to yield statistically more of the lower molecular weight fragments (37). If this latter type of action does occur, it is probably a difference in degree only and not of kind.

Although no extensive research has been carried out to correlate laboratory measurements with the performance of peptized gels, considerable information is available on a number of peptizers and their behavior.

1. Xylenol

Xylenol is used extensively as a peptizer in T.E.A.S. fuels. The commercial product, "Mixed Xylenols",

probably contains impurities since it is a more powerful peptizer than any of the pure xylenols. With the pure compounds the closeness of a methyl group to the hydroxyl group decreases the efficiency as a peptizer.

Xylenols appear to give uniform results, and permit gels to be prepared at low temperatures. The gels are somewhat less stable and have a greater temperature coefficient than those containing water or alcohol (22).

2. Alcohols

The use of alcohols as peptizers greatly reduces the temperature sensitivity of Napalm gels. These are less stable than xylenol-alcohol peptized gels at low temperatures. Fuels having a low temperature sensitivity and reasonable storage stability can be prepared using a mixture of ethyl alcohol and xylenol. These fuels would be particularly useful for tropical use (45).

The peptizing action of the various alcohols decreases with increase in length of the carbon chain, even on an equivalent molal basis.

3. Water

Gels peptized with water give shorter rod lengths and shorter ranges than those peptized with xylenol (5).

On increasing the water content of Napalm fuels a "minimum consistency" is reached at a water content equal to approximately 1/4 of the Napalm concentration. The consistency is fairly insensitive to water content at low concentrations, that is, 0.1 to 0.5% of the Napalm content (26).

4. Dinitrobenzene

The three dinitrobenzenes differ in structural formulae and dipole moment but have the same composition. Their efficacy as peptizers is identical as far as decreasing the initial viscosity is concerned, even though the dipole moments range from 6.0 to 0.0 (59). This would indicate that peptization is due to the presence of structural groups rather than to the dipole moment of the molecule as a whole.

5. Carboxylic Acids

The normal fatty acids from C_6 to C_{16} all act as peptizers. Acetic, propionic, and benzoic acids result in systems consisting of swelled lumps which do not fill the liquid. Cyclohexane, carboxylic, and benzoic acids in small quantities result in a thickening of the gel (35).

Other peptizers that have been mentioned in reports are

1. Soap,
2. Cresylic acid,
3. Phenol,
4. Hydroquinone,
5. Sulphonated Mineral Oil,
6. Tetralin.

Di- or tri- hydroxyphenols have greater peptizing power than monohydroxy phenols.

MATERIALS

1. Napalm

Napalm consists of an aluminum soap of naphthenic, oleic and cocoanut oil fatty acids prepared by co-precipitation from aqueous solution. The weight ratios of acids used are: 25% oleic acid, 25% naphthenic acid, and 50% cocoanut oil acids (35). It contains about 2% of inorganic impurities which are presumably sodium salts, basic aluminum salts and alumina; and about 1% of water (31). This water is probably held by the impurities, that is, $Na_2SO_4.10H_2O$, $Al_2(SO_4)_3.18H_2O$, $Al_2O_3.3H_2O$. The molecular weight of the acids used is 255 and the aluminum content averages 4.92% (32). This would correspond to 93% of the Napalm being in the form of the aluminum di-soap.

The specifications for Napalm are as follows (27):

"1. A 4.3% gel shall have a consistency between 75 and 150 grams after both the 21 and 44 hour tests.

2. A 4.2% gel, made with the sample to which has been added 1.5% of water on the basis of the Napalm, shall have a consistency between 35 and 80 grams after both the 24 and 44 hour tests.

3. A 4.2% gel, made in test gasoline containing 1.00% of C.P. phenol, shall have a consistency between 20 and 50 grams after both the 24 and 44 hour tests.

4. A 6.1% gel shall have a consistency between 300 and 400 grams after both the 24 and 44 hour tests.

5. An 8.0% gel shall have a consistency between 500

and 800 grams after both the 24 and 44 hour tests.

6. All of the above tests shall be in duplicate. The duplicate results of all the tests shall agree to within 50 grams, or to within the consistency limits, whichever is smaller."

2. Motor Gasoline

Grade 1, marketed as "Imperial Esso".

3. Xylenol

This is the commercial product, "mixed xylenols", manufactured by Dominion Tar and Chemicals, Limited. It is a product of coal tar and may vary somewhat in composition.

4. S.A.E. 60 Oil

Marketed as "Marvelube" by the Imperial Oil Co.

5. Soap

Marketed as "Royal Crown Soap".

6. Tetralin

7. Sodium Oleate

8. Methanol

9. Glycerol

10. Pyrogallol

11. β-Naphthol

12. α-Naphthylamine

13. Aniline

14. Benzaldehyde

The above are all standard laboratory chemicals.

APPARATUS

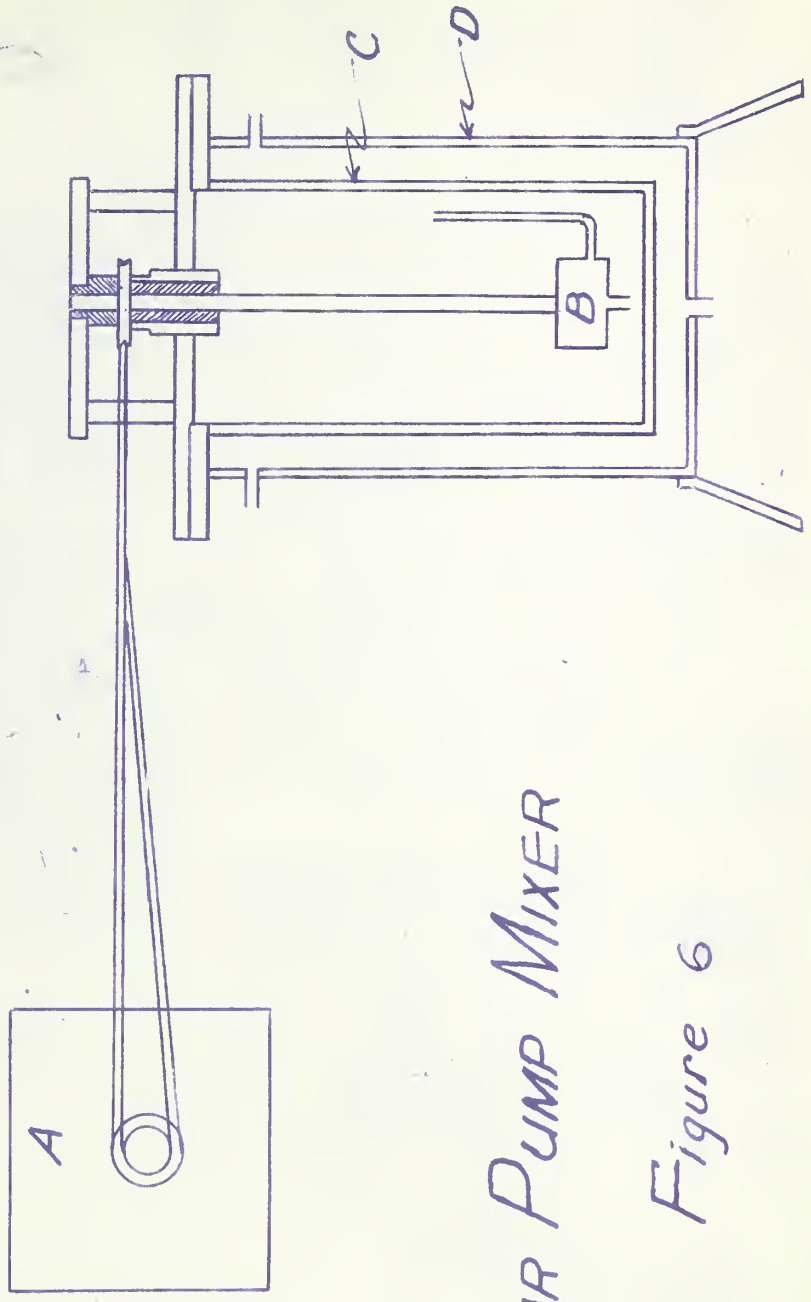
1. Mixer.
2. Ball drop viscosimeter.
3. Gardner Mobilometer.
4. Capillary pressure viscosimeters.
   (a) gas driven viscosimeter.
   (b) piston driven viscosimeter.
5. Experimental flame thrower.

1. Mixer

The mixing equipment is illustrated in Figure (6). The essential part of the mixer is a gear pump (B) driven by a 1/4 H.P. direct current motor (A). Motor speed is controlled by variation of field coil voltage. An extension of the gear pump casing is mounted on the removable top plate of the mixer tank, the shaft protrudes to carry a V-belt driven pulley. The pump is located with its intake one inch from the bottom of the tank. The discharge pipe extends half way up the container. The mixing tank (C) consists of a nine inch length of six inch steel pipe. This is surrounded by a water jacket (D) through which water is passed to con rol the temperature during mixing. The motor and mixer were mounted rigidly on a portable platform.

2. Ball Drop Viscosimeter

The ball drop viscosimeter consists of a glass cylinder and a series of calibrated steel balls. The glass cylinder was 1-1/12 inches in diameter and 8 inches deep with



GEAR PUMP MIXER

Figure 6

two marks ten centimeters apart in the middle section. The data for the calibrated steel balls is given in Table I.

TABLE I

Ball No.	Nominal Diam. in.	Av. Diameter in.	Weight gms.	Density
1	1/16	0.0622	0.01627	7.89
2	1/8	0.1241	0.1294	7.89
3	3/16	0.1868	0.4395	7.86
4	1/4	0.2502	1.0540	7.84
5	5/16	0.3117	2.0292	7.81
6	3/8	0.3742	3.5204	7.83
7	7/16	0.4369	5.5794	7.80

A sphere falling through a fluid attains a limiting velocity "u", the magnitude of which is given by Stoke's formula:

$$u = \frac{gd^2(\rho_s - \rho)}{18n} \quad (41)$$

where u = velocity

g = acceleration due to gravity

d = sphere diameter

ρ_s = density of the sphere

ρ = density of the fluid

n = viscosity of the fluid.

The calculated viscosity must be corrected for the influence of cylinder boundaries by use of Ladenburg's correction: (13)

$$\frac{\text{Viscosity (Stoke's formula)}}{\text{correct viscosity}} = (1 + 1.65\,\frac{d}{H})(1 + 2.1\,\frac{d}{D})$$

where H = height of the column of liquid

D = cylinder diameter.

Using ρ_s = 7.85, g = 980 cm/sec^2, ρ = 0.75, H = 10 cm., D = 3.61 cm., the following constants were calculated for this apparatus:

TABLE II

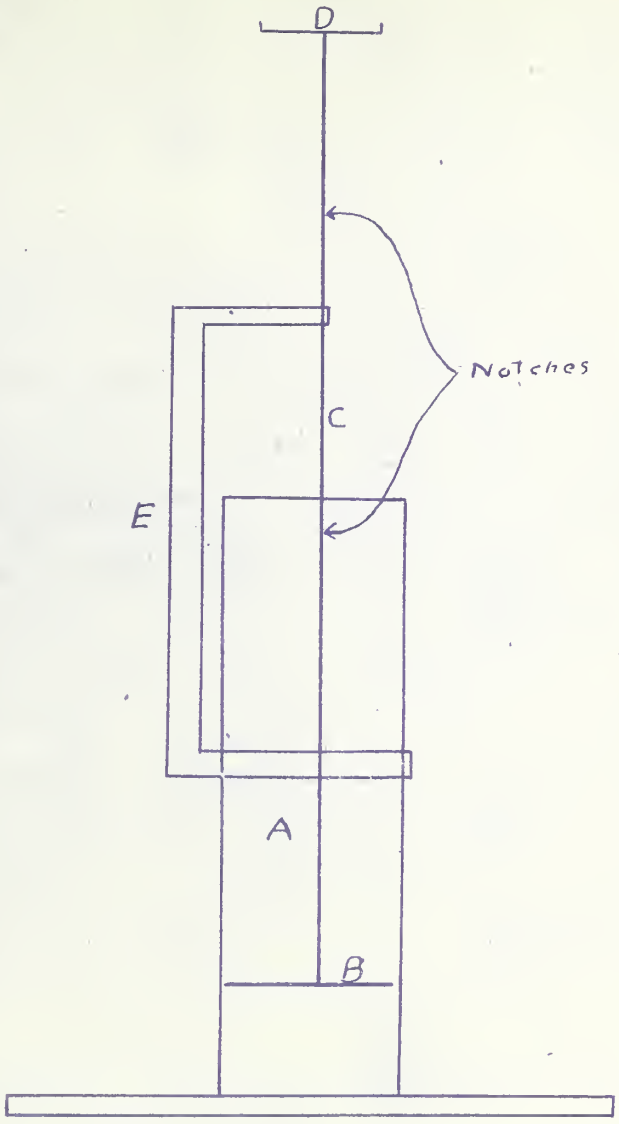
Ball No.	Viscosity	Stoke's Viscosity/correct viscosity
1	0.966t	1.12
2	3.85t	1.25
3	8.75t	1.37
4	15.7t	1.51
5	24.3t	1.65
6	35.1t	1.80
7	47.8t	1.95

where t = time of fall in seconds.

3. Gardner Mobilometer

This instrument is illustrated in Figure (7). It consists of a cylindrical steel container (A) into which the gel is placed, and a plunger that is forced through the gel. The cylinder, 1.5 inches in diameter and 9 inches high, is fitted to a triangular base plate 10 inches to a side. The plunger consists of a metal plate (B) with four 1/4 inch openings, that fits into the cylinder, and a hollow metal rod (C). This rod is notched in two places ten centimeters apart on the upper

FIGURE 7



GARDNER MOBILOMETER

section. A pan (D) for weights is fitted to the upper end of this rod. The plunger assembly weighs approximately 100 grams. The weights are approximately 500 grams (2), 200 grams (2), 100 grams and 50 grams. The rod guide (F) is clamped rigidly to the cylinder. The relation of time of fall through 10 cm. and weight is determined. The results are expressed graphically as load vs. time on log-log paper.

4. Capillary Pressure Viscosimeters

(a) Direct gas pressure drive viscosimeter

This apparatus, with the equipment used to photograph the jet, is shown in Figure (8). The viscosimeter proper consists of a twelve inch length of standard 1-1/4 inch iron pipe (E) into which is fitted a capillary (G). This storage cylinder is surrounded by a water jacket (F) for maintaining the gel at constant temperature. Water is supplied to this jacket by means of the constant head device (I) through a tubular type rheostat (H) which serves as a heater. Approximate temperature control is obtained by regulating the flow of water through the apparatus, and fine adjustment by means of the rheostat. The viscosimeter barrel is connected by means of a 1/4 inch standard iron pipe to a tank of liquid carbon dioxide through a surge tank (B) and a reducing valve (A). Low pressures are measured by means of a mercury manometer (D), and high pressures by a Bourdon tube gauge (C). Three different Bourdon gauges are used with ranges of 0-30, 0-100, and 0-300 P.S.I. Purge lines are placed as indicated to facilitate operation and pressure control. Efflux is measured in a previously weighed beaker placed

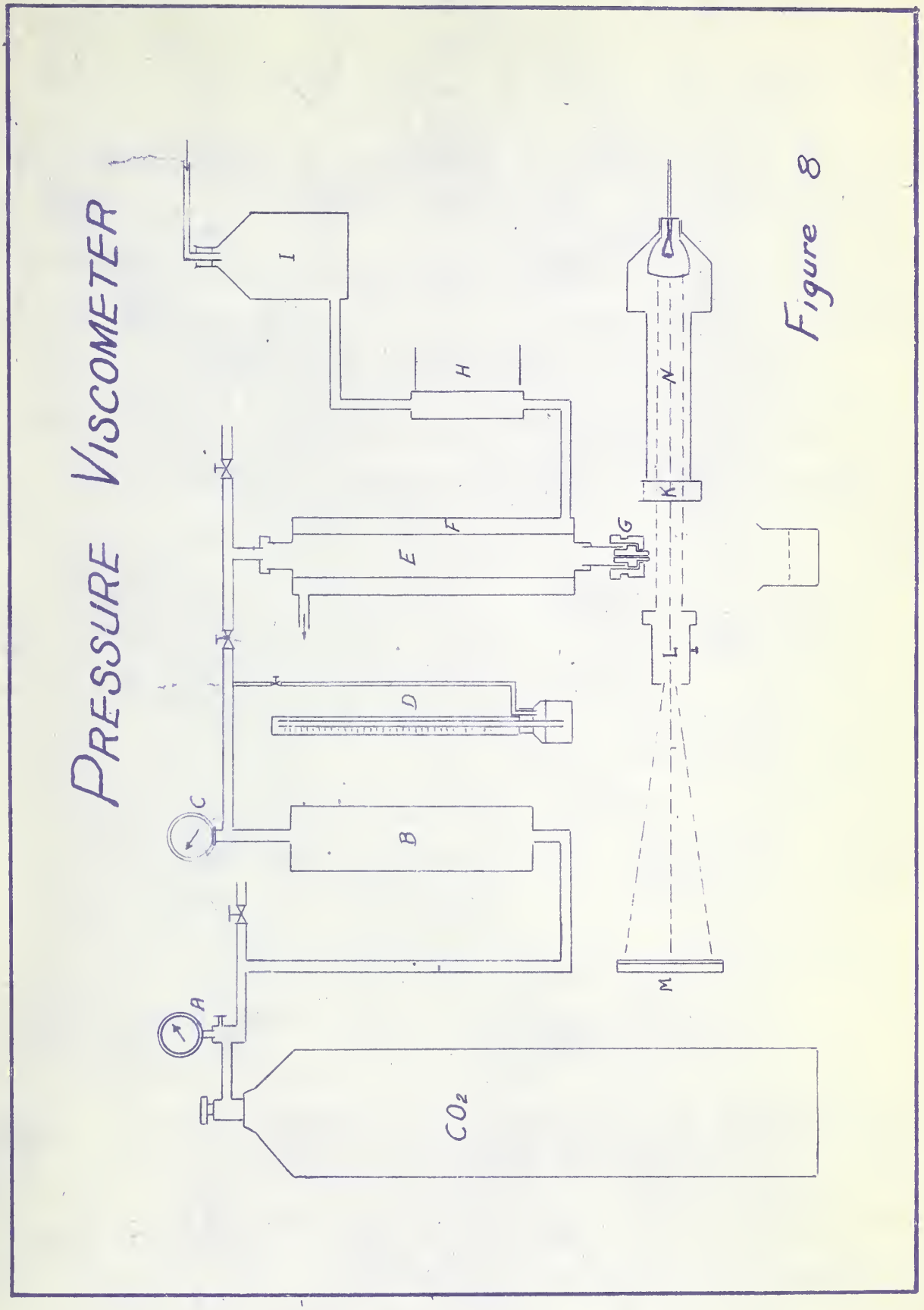


Figure 8

directly beneath the capillary.

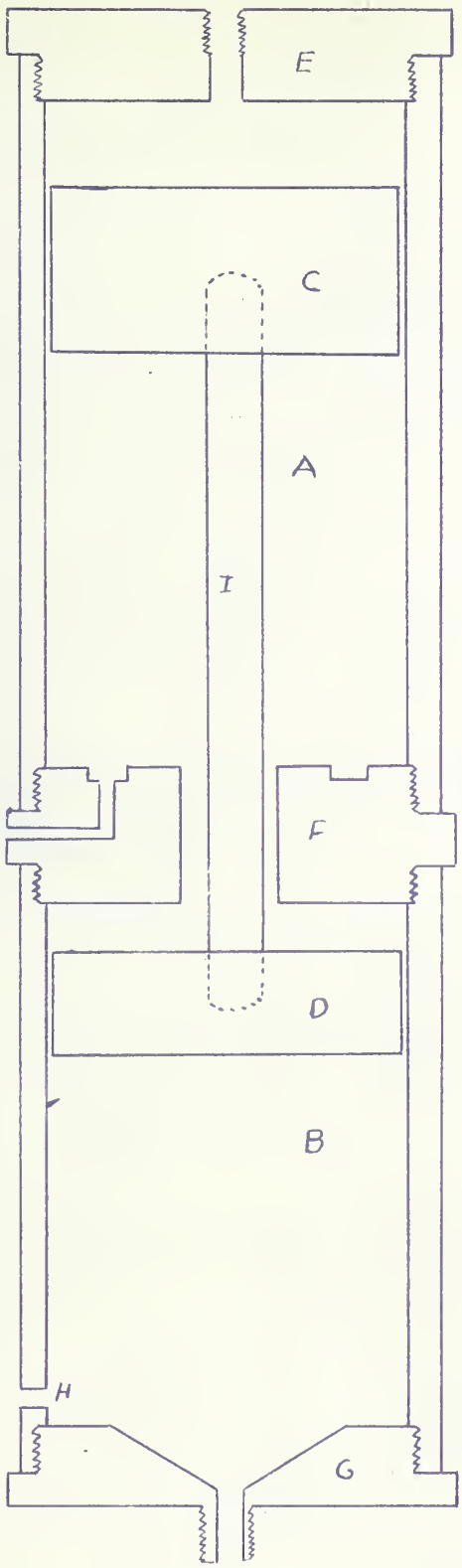
This apparatus works very well with thin gels, but is not suited for testing thicker gels because of channelling.

(b) Piston drive viscosimeter

The piston drive viscosimeter is illustrated in Figure (9). This apparatus was designed to overcome the difficulty encountered with the gas driven viscosimeter in regard to channelling. It consists essentially of two cylinders fitted with a piston assembly. Gas pressure is applied to the piston (C) in the gas cylinder (A) and transmitted through the connecting rod (I) to the piston (D) in the fluid cylinder (B). The cylinders were machined from extra heavy steel pipe to an inside diameter of 2-3/16 ± 0.002 inches with 2-3/8 inch threads on the inside at both ends. The length of the liquid cylinder is 9-5/8 inches; that of the gas cylinder 9-7/8 inches. The fluid piston is wound with copper tubing through which water is passed to maintain constant temperature. The pistons are standard Austin motor car pistons turned down to 2-3/16 - 0.003. The gas piston, but not the liquid piston, is fitted with rings. Further, the skirt on the liquid piston was removed to give a height of 1-9/16 inches. The connecting rod, cut from a 3/4 inch square bar, is 10-7/8 inches long, and is joined to the pistons by means of the original wrist pins. The screw tap (E) fitting into the gas piston is tapped to fit a standard 3/8 inch pipe. The central union (F), which screws into the gas and liquid cylinders, was designed to maintain alignment

FIGURE 9

PISTON DRIVE VISCOSIMETER



of the two cylinders. It was bored to a one inch central opening to pass the connecting rod. The cap (G) fitting into the liquid cylinder has an opening tapering from 1-1/2 inches to 21/64 inches over a distance of 7/8 inches. The nipple extends for a distance of one inch past the base of the cap; this has an inside diameter of 21/64 inches, and is threaded on the outside with a standard 1/2 inch S.A.E. thread. These three fittings are drilled to permit the use of a 3/8 inch dolly bar. However, the central union is only hand tight. A pressure tap (H) to fit a 1/4 inch steel tube is located near the bottom of the liquid cylinder. The viscosimeter is held in place on the stands by means of two U bolts placed around the gas cylinder. This permits easy removal of the liquid cylinder for filling and cleaning. Pressure is applied to the gas cylinder from a tank of liquid carbon dioxide through a reducing valve and a surge tank. Purge lines are placed as shown in figure (8) for the direct gas pressure drive viscosimeter.

The capillaries used in the viscosimeter have the following dimensions:

TABLE III

Capillary No.	Length in inches	Diameter in inches
1	0.741	0.0234
2	0.997	0.0480
3	1.27	0.0632

Using the capillary viscosimeter, the viscosity is calculated from Poisseuille's equation:

$$\eta = \frac{\pi r^4 P}{8Ql} \quad (16)$$

where r = radius of the capillary,

P = effective pressure causing flow,

Q = volume rate of flow,

l = length of the capillary.

Corrections must be applied to the observed pressure for:

1. The kinetic energy loss at entrance to the capillary

   K.E. loss at entrance = $\frac{KV^2}{2g}$ (40)

   where K = a constant calculated from the radius of the capillary,

   V = linear velocity,

   g = acceleration due to gravity.

2. The kinetic loss at exit from the capillary

   K.E. loss at exit = $\frac{Q^2}{\pi^2 r^4 g}$ (42)

Each value of velocity corresponds to a rate of shear given by the equation

$$\text{Rate of shear} = \frac{4}{\pi r^3} \quad (38)$$

5. Photographic Apparatus

The jet from the capillary is photographed using the apparatus illustrated in Figure (8). The optical system is essentially a shadow projector. The light source is a 100 watt bulb enclosed in a light tunnel (M). A water bath (N) is

is placed between the tunnel and the jet to absorb the radiant heat from the long beam. The lenses (L) are arranged to enlarge the jet and a millimeter scale clamped on the capillary holder, approximately seven times. The image is projected into a screen consisting of sensitized paper about three feet from the jet.

Figure (10) shows an actual photograph of the jet; (a) is the capillary exit, and (b) the section of maximum enlargement. If we assume that the diameter of the jet increases linearly with the distance from the capillary, that is, that r-a = Kx, where "r" = diameter at a distance "x" from the capillary, "a" is the diameter of the capillary, and "K" is the proportionality constant, then $V_x = V \frac{a^2}{(Kx + a)^2}$, where V = velocity at section "a" and V_x is the velocity at section x. The average velocity over the region is determined by integration:

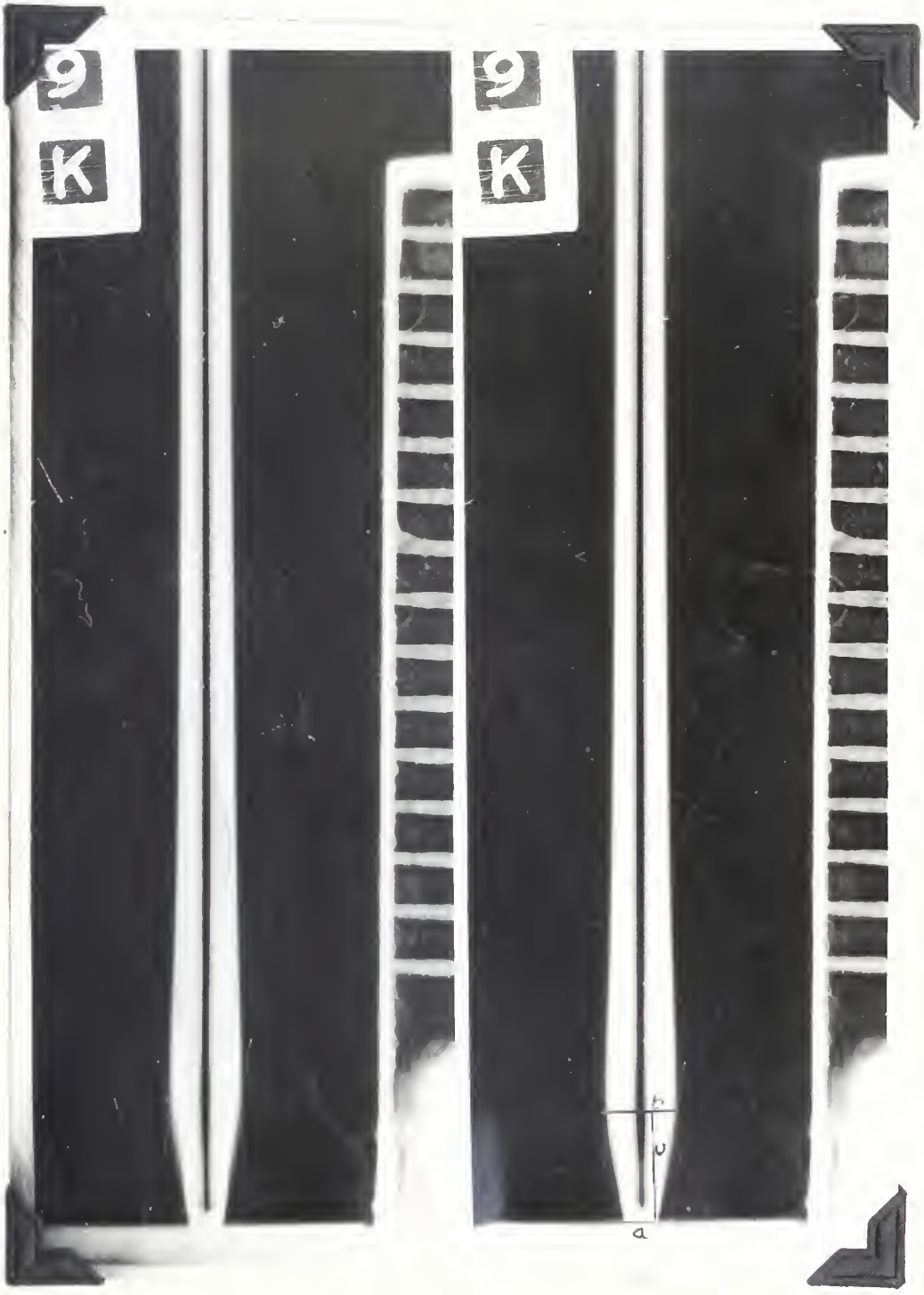
$$V_{av.} = \frac{Va^2}{x_1} \int_0^{x_1} \frac{1}{(Kx + a)^2}\, dx$$

$$= \frac{Va^2}{x_1} \left[\frac{-1}{K(a + Kx)} \right]_0^{x_1}$$

which reduces to $V_{av.} = \frac{aV}{b}$, where "b" is the diameter at maximum enlargement. The healing time is computed from the relation, healing time = C/V_{av}, where C = distance from the capillary to the point of maximum enlargement.

Tangents drawn to the two portions of the jet permit location of the point of maximum enlargement. Measurements are made by use of dividers and scale to the nearest 1/100 of an inch. In making computations, these measurements must

Figure 10

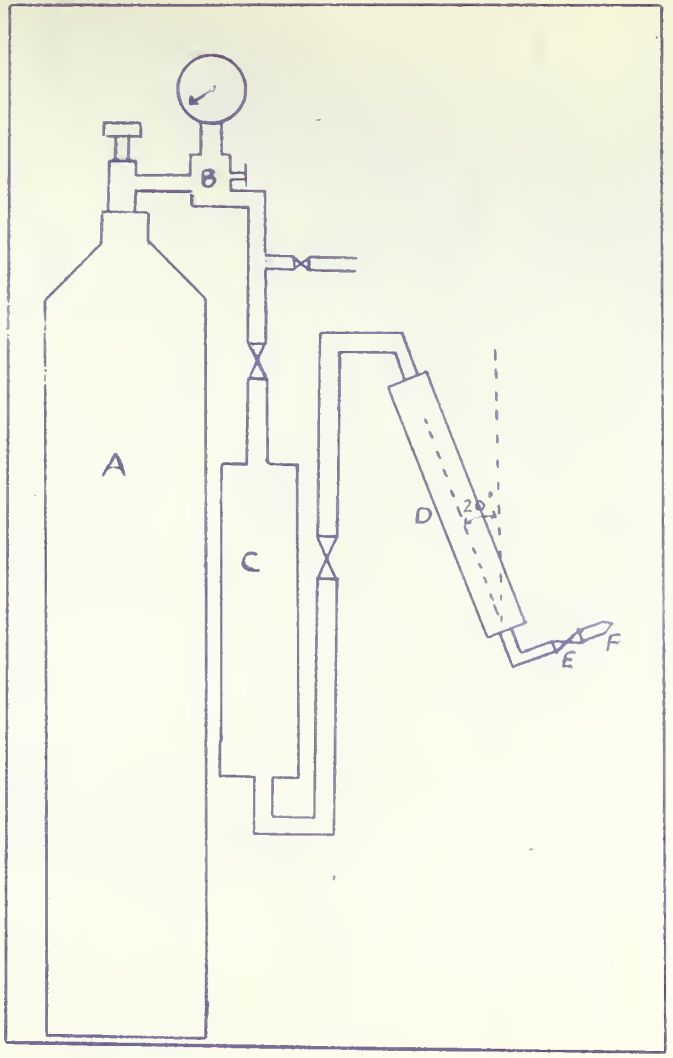


be reduced by the magnification factor which can be obtained from the millimeter scale which is photographed with the jet.

6. Model Flame Throwers

The gas driven flame thrower is illustrated in Figure (11). It consists of a gel cylinder and a pressure tank. The gel cylinder (D), constructed from a section of standard 1-1/2 inch pipe 12 inches long, is connected through a surge tank (C) and reducing valve (B) to a tank of liquid carbon dioxide (A) by means of standard 1/4 inch pipe. The gel cylinder is mounted rigidly to the stand at an angle of 20° to the vertical. A 1/4 inch nipple and ell are connected to the bottom of the cylinder, and to this a quick opening Nordstrom valve (E). The nozzle (F) screws directly into the valve.

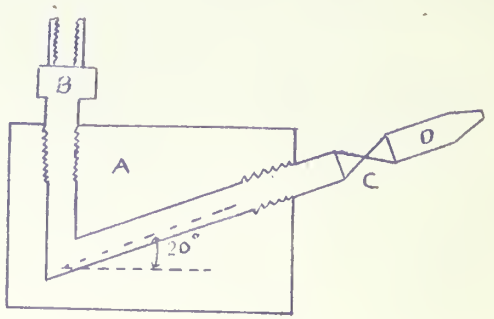
As happened in connection with the capillary viscosimeter measurements, channelling occurred in the direct gas driven model flame thrower. To overcome this difficulty the piston driven viscosimeter was used as a flame thrower for thick gels. When used in this way the capillary holder is replaced by the nozzle attachment illustrated in Figure (12). It consists of an iron block (A) into which two holes have been drilled at an angle of 70°. This is connected to the liquid cylinder by means of a 1/4 inch male-female union (B). The female section was tapped to 1/2 inch s.i.p. thread. The nozzle (D) and Nordstrom valve (C) are joined to the block by a 1/4 inch nipple.



FLAME THROWER

FIGURE 11

FIGURE 12



Flame Thrower Attachment

EXPERIMENTAL PROCEDURE

Preparation of Gels

The preparation of large batches of fuel was standardized as much as possible in order to get reproducibility of batches. All weighings were made to the nearest 1/10 gram, and volumes of gasoline were measured to the nearest 10 c.c. The ingredients were always added in the same order, that is, Napalm, peptizer (when used), gasoline. The weights of Napalm and of peptizer were computed as a percentage of the weight of gasoline rather than as a percentage of the total weight.

Mixing was done by hand until gelation started, and then by means of the gear pump mixer until the gel was visibly homogeneous. For the first fifteen minutes the delivery pipe of the pump was removed, and then replaced for the remainder of the stirring time. The temperature of mixing was maintained at 20° to 25°C.

Measurement of Viscosity

1. Gardner Mobilometer -

A special viscosity experiment was made with the Gardner Mobilometer to determine the behavior with a Newtonian liquid. The viscosity test on S.A.E. 60 oil was conducted outside in the shelter of the buildings when the temperature was about -18°C. The oil was placed in the Mobilometer and set outside for somewhat over an hour, and "worked" every

fifteen minutes in order to obtain uniform temperature. The actual run required about one half hour.

All other Gardner Mobilometer tests on gels were made at room temperature. After filling, assembling, and "working", a weight was used which was high enough to require approximately one second time of fall. The weight was then decreased in amounts depending on the viscosity of the gel; for thin gels it was decreased by 50 grams, and for thicker gels 200 grams down to 50 grams until the time of fall was approximately 100 seconds. The data was plotted immediately on log-log paper as load versus time and any readings definitely in error repeated.

2. Capillary Viscosimeter and Jet measurements

Before making viscosity and melting time measurements, the circulating water in the water jacket was adjusted to 25 ± 0.2°C. The viscosimeter was opened and gel introduced into the cylinder until filled to a definite height, which was the same in all experiments. It was desirable to have the same height of gel in all experiments in order to have approximately the same static head in all determinations. This was unnecessary when using the piston driven viscosimeter since the pressure was measured at the capillary entrance and was not the gas pressure used. The cylinder was closed and gas introduced until the desired pressure was reached. In all cases this pressure was such that the enlarged section of the jet "broke away" from the end of the capillary. The gel discharged from the capillary was collected in a previously weighed 400 c.c. beaker over a

period of 100 seconds. The weight of efflux was determined immediately to reduce errors caused by evaporation of the gel. Each determination was run in duplicate. The capillary was inspected and cleaned after each run. The projection of the jet was focused accurately on the screen, the light turned off, and the sensitized paper put into place. The paper holder was so constructed that only one half of the paper was exposed at one time. After fifteen seconds exposure the procedure was repeated using the unexposed portion of the paper. Hence, two photographs of the jet were obtained in each run. Since all determinations were made in duplicate at least, this gave a minimum of four pictures of the jet from which to obtain healing time measurements. In many cases, particularly with thick gels, there was considerable vibration of the jet and it is believed that four photographs are necessary in order to obtain a sufficient degree of accuracy in the measurement of healing time. Measurements of minimum width and distance to maximum width were taken to the nearest 1/100 inch and reduced by the magnification factor.

3. Ball drop viscosimeter

The ball drop viscosity determinations were made at room temperature. These were done with duplicate samples to check the homogeneity of the gel. No special attempt was made to centre the ball accurately in the cylinder or to avoid parallax errors. A series of balls of different diameters was used with each gel, starting with the largest ball. In order to allow the gel structure to reform after being disturbed by the passage of one ball, the succeeding

ball was not placed in the gel until the preceding ball had fallen at least two inches. In no case was this time interval less than 30 seconds. This, apparently, gave the gel sufficient time to heal. The determination required about one half an hour. Because of the shape of the cylinders, it is doubtful if sufficient evaporation would take place in this length of time to appreciably affect the viscosity of the main body of the gel.

The average time of fall for balls of the same size in duplicate samples was used to compute a value for viscosity. This value was then taken with the values obtained by the use of balls of other sizes to yield an "average" viscosity value.

Field Tests

The field performance of the gels was studied by use of the model flame throwers. The tests were conducted outside in the shelter of nearby buildings to eliminate as far as possible the effects of wind. Further, to eliminate this variable, shots were made only when the wind velocity was negligible or low.

The cylinder was filled with gel and pipe connections made through a surge tank and reducing valve to a pressure cylinder of liquid carbon dioxide. The pressure was adjusted to the desired value, the Nordstrom valve opened and the gel allowed to discharge. Ignition was obtained by means of a hydrogen or methane jet burning continuously at the nozzle tip. Immediately after the shot the measurement of maximum range was made. The shots were repeated using

pressures of 75, 100, and 125 p.s.i.

Since the properties of napalm gels change with time, the various tests were conducted so as to eliminate, as far as possible, this variable. Whenever possible, the gel was allowed to age for a period of weeks and the measurements of viscosity, Gardner consistency, healing time, and field performance were carried out within a few days of one another.

RESULTS

1. Gardner Mobilometer Test on a Newtonian Liquid

In an attempt to establish a basis for the interpretation of Gardner Mobilometer data it was decided to make a run on a Newtonian liquid. Since the Gardner Mobilometer can be used only with liquids of high viscosity, none of the ordinary liquids at ordinary temperatures could be used. That finally chosen was S.A.E. 60 oil, which has a high viscosity at low temperature. The data for this test at about -18°C are presented in Table IV and represented graphically in Figures (13) and (14). It will be noted that in Figure (13) the slope is greater than -1, and in Figure (14) the graph does not pass through the origin, as would be expected of a Newtonian liquid.

2. Gardner Mobilometer Data and Viscosity Changes with Rates of Shear

Gardner Mobilometer data and the viscosity at different rates of shear were obtained on a series of gels. The data are given in Tables V and VI and represented graphically in Figures (15), (16), and (17). It will be noted that the viscosity is a function of the rate of shear, the viscosity decreasing markedly as the rate of shear increases. This is characteristic of non-Newtonian liquids. Another feature worthy of notice is that the plot of viscosity-rate of shear on log-log paper is parallel, or nearly so, to the corresponding plot of Gardner data, that is, load-time on log-log paper.

TABLE IV.

Gardner Mobilometer test on Oil

S. A. E. 60. at about -18 C

Load (in grams)	Time (in seconds)
1500	5.2
1300	6.8
1100	8
900	10
800	12
700	14
600	17
500	20
400	27
300	38
250	49
200	67
150	95

TABLE V

Gardner Mobilometer Data on Gels; 15 -5, 273, 12 -2.

15 - 5, 15 % Napalm, 0 % Xylenol.

273, 5 % Napalm, Prepared at Suffield.

12 - 2, 12 % Napalm, 2 % Xylenol.

	(a)		(b)		(c)	
Code No.	15-5		273		12-2	
	Load gms.	Time sec.	Load gms.	Time sec.	Load gms.	Time sec.
	1600	1.4	800	0.8	1600	2.0
	1500	1.6	700	1.0	1400	2.6
	1400	1.8	600	1.4	1200	5.6
	1300	2.2	500	1.8	1100	8.4
	1200	2.6	400	3.0	1000	11
	1100	3.2	350	4.4	900	16
	1000	4.4	300	5.2	850	18
	900	6.0	250	9.0	800	20
	800	8.0	200	17	750	23
	700	11	150	37	700	25
	600	15	100	110	650	27
	550	18			600	32
	500	22			550	36
	450	27			500	41
	400	34			450	48
	350	42			400	58
	300	56			350	74
	250	80			300	95

TABLE VI

Viscosity - Rate of Shear Data. Gels: 15 - 5, 273, 12 - 2.

	(a)		(b)		(c)	
Code No.	15 - 5.		273.		12 - 2.	
	Visc. Poise	Shear Rate. $secs^{-1}$	Visc. Poise	Shear Rate. $secs^{-1}$	Visc. Poise	Shear Rate. $secs^{-1}$
	350	75	28.3	650	600	82.4
	96	490	21.5	1260	384	171
	59	1050	15.7	2850	168	698
	43	2120	12.8	4660	88.9	1980
	32	3860	10.4	5490	56.4	2360
	20.5	8400	7.13	11000	41.5	3940
	16	13000	4.9	22200	29.2	7350
	14.5	19700	4.2	39700	20.3	11900
	12	29200	3.6	62500	17.5	15300
	11.3	36900			14.1	23400
	10.7	45200			12.3	31200
					10.4	40600
					8.7	62700

3. Ball Drop Data

In order to obtain the viscosity of the various gels in a reasonable time by means of falling spheres, a series of spheres of different diameters were required. Since the true value of initial viscosity is obtained only if a definite ball size is not exceeded, a number of determinations of viscosity were run using balls of different diameters in order to determine this upper limit. These dataare presented in Table VII.

For thicker gels, using the balls available, the viscosity is a constant, independent of the ball size. For the thinner gels the viscosity is definitely dependent on the ball size but reaches a limiting value as the ball diameter is reduced.

4. Healing Time

The HT/VD data for a gel containing 15% Napalm and 5% xylenol are presented in Table VIII as an example showing the reproducibility of the data.

TABLE VIII

Gel No.	Plate No.		(p.s.i.) Pressure	Efflux Volume c.c./ 100 sec.	HT secs^{-1} x 10^{-3}	VD ft^2/$_3$ sec x 10^{-3}	HT/VD
15-4	M-1	A	107	155.8	0.416	13.9	0.0299
		B			0.416	13.9	0.0299
	M-2	A	107	119.2	0.387	12.5	0.0309
		B	Jet plugged				
	M-3	A	108	125.8	0.375	12.3	0.0305
		B			0.375	12.3	0.0305
	M-4	A	108	136.9	0.408	13.6	0.0300
		B			0.408	13.6	0.0300
						average =	0.0302

Table VII.

Ball Drop data.

(a). Gel 9 - 5. 9% Napalm, 1.25% Xylenol.

Ball diam. inches	Time of fall seconds (1)	(2)	(3)	Av.	Viscosity: (Stokes), poise	(corr.)
7/16	125	119	132	125	5970	3070
6/16	166	170	180	172	6040	3360
5/16	210	222	220	217	5250	3200
4/16	326	299	327	318	4970	3290
3/16	514	554	516	528	4720	3370
2/16	1095	1060	1135	1097	4160	3320
					Average	3270
					Average Deviation	2.8 %

(b). Gel 7 - 5. 7% Napalm, 1% Xylenol.

5/16	25	368
4/16	64	664
3/16	126	805
2/16	380	1150
1/16	1370	1180

(c). Gel 7 - 16. 7% Napalm, 1.5 ∝ Naphthylamine.

7/16	1.3	31.9
6/16	3.0	57.6
5/16	11.3	166
4/16	37	385
3/16	89	567
2/16	207	637
1/16	849	731

5. Napalm Gels

Knudsen and Sereda (20) have presented data correlating healing time and range for straight Napalm gels up to a Napalm concentration of 6%. The data for gels of higher concentration are presented in Table IX. Inspection will show that the behavior differs from that of gels containing less than 6% Napalm in degree only and not in kind.

TABLE IX

Napalm Gels

% Napalm	B.D. Viscosity (poise)	100" Gardner (grams)	1/10" Gardner (grams)	Gardner Slope	HT/VD	Range (ft) (p.s.i.) 75	100	125
7	8940	440	2,800	0.27	0.0930	43	63	83
9	32500	700	3,000	0.2	0.0634	51	57	77
12	77500	1,250	3,400	0.14	0.020			25

A 15% Napalm gel was prepared but it was too viscous to determine the viscosity by use of the balls available, and also too viscous to be run in the mobilometer.

6. Field Performance of Napalm Gels

The field performance of straight Napalm gels in a model flame thrower has been correlated with HT/VD. A series of tests were carried out at Sunfield experimental station using a combat flame thrower (Wasp Mk. II). These data were studied and a correlation with viscosity sought. These data are presented in Table X. An examination of Figures (19) and (21) reveals that maximum effective range can be predicted

TABLE X

Laboratory and Field Data for Napalm Gels.

Gel No.	Comp % Napalm	Ball Drop secs.	Gardner	H. T. V. D.	Press. lbs.	Elev.	Range MER.	L	Jet	
336	7.0	Prepared		0.119	250	15	150	30	80	A
		5/32"	0.1" load		250	10	175	30	80	B
		850-990	2200		250	15	150	30	80	B
		890-980	2100		250	10	Channelled			
			100" load							
			450							
			460							
		Fired	0.1" load							
		1/2"	3000							
		90-205	2100							
		73- 95	1800							
		30- 47	100" load		Prepared: Sept. 14, 1944					
			420		Fired: Oct. 20, 1944					
			400							
			400							
337	7.5	Prepared		0.096	250	10	125	25	110	B
		5/32"	0.1" load		250	10	122	25	100	A
		995-1190	2500		250	15	Channelled			
		1080-1180	2000		250	15				
		1/2"	100" load							
		105-135	480							
		135	520							
		Fired								
		1/2"	0.1" load							
		215	2400							
		210	2150							
		266	1900		Prepared: Sept. 14, 1944					
			100" load		Fired: Oct. 19, 1944					
			500							
			600							
			490							
338	6.0	Prepared		0.145	250	10	125	30	70	A
		5/32"	0.1" load		250	10	120	30	70	B
		605-735	2000		250	15	132	30	70	B
		560- 660	2000		250	15	135	30	70	A
		1/2"	100" load							
		13-29	320							
		20	320							
		Fired								
		5/32"	0.1" load							
		1110	2100							
		840	1900							
		960	1700		Prepared: Sept. 14, 1944					
		1/2"	100" load		Fired: Oct. 20, 1944					
		20	280							
		13	310							
		17	290							

TABLE X (continued)

Gel No.	Comp % Napalm	Ball Drop secs.	Gardner	H. T. / V. D.	Press. lbs.	Elev.	Range MER	Range L	Range Jet	
339	5.5	Prepared	0.1" load	0.232	250	10	125	30	60	A
		5/32"	1650		250	10	120	30	60	B
		270-335	1900		250	15	135	30	60	B
		265-350	100" load		250	15	145	30	60	A
			180							
			180							
		Fired	0.1" load							
		5/32"	1200							
		280-540	1100		Prepared: Sept. 14, 1944					
			1100		Fired: October 20, 1944					
			100" load							
			210							
			190							
			195							
340	5.0	Prepared		0.247	250	10	130	30	60	A
		5/32"	0.1" load		250	10	140	30	40	B
		190-210	1500		250	15	140	30	40	B
		145-210	1500		250	15	140	30	40	A
			100" load							
			140							
			140							
		Fired	0.1" load							
		5/32"	1100							
		195-435	1100							
		155-290	1050							
		280-455	100" load		Prepared: Sept. 14, 1944					
			135		Fired: Oct. 20, 1944					
			145							
			145							
341	4.5	Prepared		0.396	250	10	120	30	50	A
		5/32"	0.1" load		250	10	120	30	50	B
		36-65	1100		250	15	120	30	50	B
		30-66	1150		250	15	120	30	50	A
			100" load							
			100							
			90							
		Fired								
		5/32"	0.1" load		Prepared: Sept. 15, 1944					
		13-27	1300		Fired: Oct. 20, 1944					
		19-27	1250							
		15-24	1250							
			100" load							
			105							
			90							
			90							

TABLE X (continued)

Gel No.	Comp. % Napalm	Ball Drop Secs.	Gardner	H. T. / V. D.	Press. lbs.	Elev.	Range MER	Range L	Range	Jet
342	4.0	Prepared	0.1" load	0.534	250	10	115	30	50	A
		5/32"	1100		250	10	110	30	50	B
		12-30	1100		250	15	145	30	50	B
		17-25	100" load		250	15	145	30	50	A
			70							
			70							
		Fired								
		5/32"	0.1" load							
		6- 8	1100							
		7-12	1100							
		7-16	1130							
			100" load		Prepared: Sept. 15, 1944.					
			80		Fired: Oct. 20, 1944					
			80							
			80							
343	3.25	Prepared								
		5/32"	0.1" load	0.820	250	10	95	30	30	A
		1.7-2.4	800		250	10	95	30	30	B
		2.4-3.4	800		250	15	95	30	30	B
			100" load		250	15	95	30	30	A
			35							
			35							
		Fired								
		5/32"	0.1" load							
		1.5-2.0	680		Prepared: Sept. 15, 1944					
		1.0-1.6	100" load		Fired: Oct. 20, 1944					
		1.2-2.0	36							

from either Gardner consistency or HY/VD measurements. Another relationship that may be useful and more precise is that of unbroken jet length with HT/VD.

7. Xylenol Peptized Gels

Since xylenol is used widely as a peptizer in F.R.A.S. fuels, and since considerable work has been done on xylenol peptized Napalm gels, it was decided to investigate this type of gel with a view to extending the relationships established for the prediction of field performance of straight Napalm fuels to cover peptized fuels. Data for 7, 9, 12 and 15% gels are presented in Table XI. An examination of Figures (28) and (29) reveals that the relationship between HI/VD and range still holds but that between Gardner consistency and range does not.

8. Peptized 7% Gels

A number of gels containing 7% Napalm and various peptizers were prepared and tested. The results are given in Table XII and presented in Figure (35). The correlation between HT/VD and range holds good for most, but not all, of these gels.

TABLE XI

Xylenol Peptized Gels

% Xylenol	B.D. Viscosity (poise)	100" Gardner (grams)	1/10" Gardner (grams)	Gardner Slope	HT/VD	Range - ft. 75 psi.	100 psi.	125 psi.
7% gels								
0	8,940	430	2,800	-0.27	0.0930	43	63	83
0.25	5,940	300	2,100	-0.28	0.153	60	75	93
0.5	3,260	230	1,700	-0.29	0.187	65	93	98
1.0	1,170	140	2,000	-0.38	0.227	59	82	--
1.5	317	58	1,100	-0.43	0.281	60	81	98
9% gels								
0	32,500	780	5,000	-0.19	0.0634	31	57	77
0.5	7,500	600	3,200	-0.24	0.0581	36	65	--
0.75	2,450	300	3,200	-0.29	0.0739	39	61	--
1.0	1,470	230	1,800	-0.30	0.096	45	67	86
1.5	1,350	190	2,600	-0.38	0.094	42	63	--
2.0	527	120	2,200	-0.42	0.128	56	83	89
12% gels								
0	77,500	1,250	4,400	-0.14	0.020	--	--	25
1	9,880	640	5,000	-0.30	0.0225	--	46	64
2	5,190	290	4,000	-0.38	0.039	30	63	70
3	2,010	320	2,800	-0.32	0.0445	--	59	78
5	832	130	4,400	-0.50	0.093	56	76	--
15% gels								
1	65,400	1,510	3,600	-0.13	0.0203	--	--	35
3	8,000	730	6,400	-0.3	0.0223	--	--	40
5	3,370	440	4,000	-0.32	0.0302	--	31	56
9	1,820	270	3,700	-0.38	0.037	40	60	80

TABLE XII

7% Gels with Various Peptizers

Code No.	% Peptizer	Viscosity (poise)	100" Gardner	1/10" Gardner	Gardner Slope	HT/VD	Range - ft. 75 psi.	100 psi.	125 psi.
7-7	1.5 xylenol	312	58	1,100	0.43	0.281	66	81	98
7-8	1.5 water	141	33	1,056	0.50	0.306	62	80	--
7-9	1.5 tetralin	10,800	590	2,100	0.24	0.081	50	72	84
7-10	1.5 soap	--	--	--	--	--	--	--	--
7-11	1.5 sodium oleate	--	--	--	--	--	--	--	--
* 7-12	1.5 methanol	17.6	--	--	--	0.547	58	79	--
7-13	1.5 glycerol	1,400	190	1,480	0.29	0.125	59	71	96
7-14	1.5 pyrogallol	--	--	--	--	--	--	--	--
7-15	1.5 naphthol	367	57	1,440	0.47	0.230	65	80	--
7-16	1.5 naphthylamine	756	89	1,650	0.43	0.210	72	95	--
7-17	1.5 aniline	125	35	800	0.45	0.345	65	--	--
7-18	1.5 benzaldehyde	7,870	270	1,900	0.27	0.145	57	68	85
7-19	0.75 methanol	72	17	3,100	0.75	0.307	55	67	--
7-20	0.25 pyrogallol	85	7.1	1,000	0.72	0.910	65	--	--

7-10 A grey precipitate formed after standing for a few days, leaving a supernatant liquid that was not thickened.

7-11 Grey flocculent precipitate formed after standing for two days, slight thickening of supernatant liquid.

* 7-12 Grey flocculent precipitate formed after standing for two days. Supernatant liquid thickened considerably and saved for testing.

7-14 Gel structure destroyed while in mixer. Dark grey precipitate formed. Supernatant liquid nearly black, slightly thickened.

DISCUSSION

1. Gardner Mobilometer Test on S.A.E. 60 Oil

According to definition, a Newtonian liquid has a constant viscosity regardless of the rate of shear. In an instrument such as the Gardner Mobilometer the time of fall through such a liquid should be consistent with constant viscosity. There is some question as to whether the behavior of the Gardner Mobilometer is analogous to that of a falling ball or to that of flow through an orifice. If it is analogous to that of a falling ball, then the relation between time of fall and load should be identical with the relation between time of fall and ball density for balls of the same dimension, that is, the time of fall should be inversely proportional to the load; the slope of the log-log line would be -1. If it is analogous to flow through an orifice, the time of fall would be inversely proportional to the square root of the load and the slope of the log-log line would be -1/2.

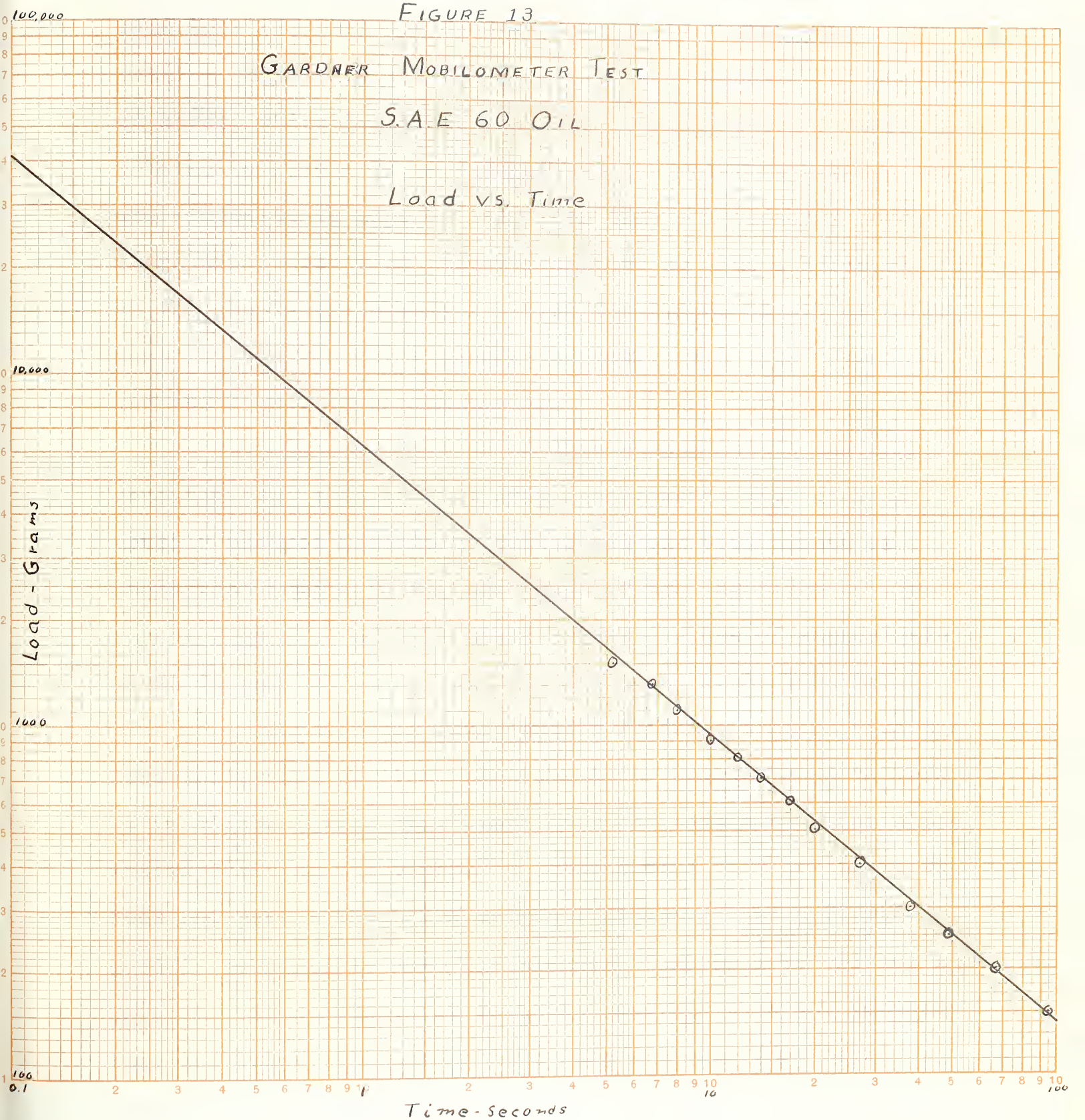
The data in Table IV is illustrated graphically in Figure (15) as the load versus time on a log-log graph. This line has a constant slope of -0.84. Assuming that the viscosity is constant this may be interpreted as indicating that the behavior of the Gardner Mobilometer is a combination of that of a falling body and flow through an orifice. This, however, seems unlikely when we consider the behavior of gels that are undoubtedly thixotropic or non-newtonian. For these gels the load-time relationship plotted on log-log

FIGURE 13

GARDNER MOBILOMETER TEST

S.A.E 60 OIL

Load vs. Time



paper has also a constant slope.

A more likely interpretation is based on the assumptions (1) that the Gardner Mobilometer behaves as a falling body, and (2) that viscosity is a function of the rate of shear, which is related to rate of fall, which in turn is related to load. If we assume that the relation between load and viscosity is exponential, then time = K (load)^{x}/ load, where K = constant of proportionality, or time = K/(load)$^{1-x}$. On this basis presumably x = 0.16 for S.A.E. 60 oil at -18°C, that is, the viscosity changes slightly with rate of shear and the liquid is non-Newtonian.

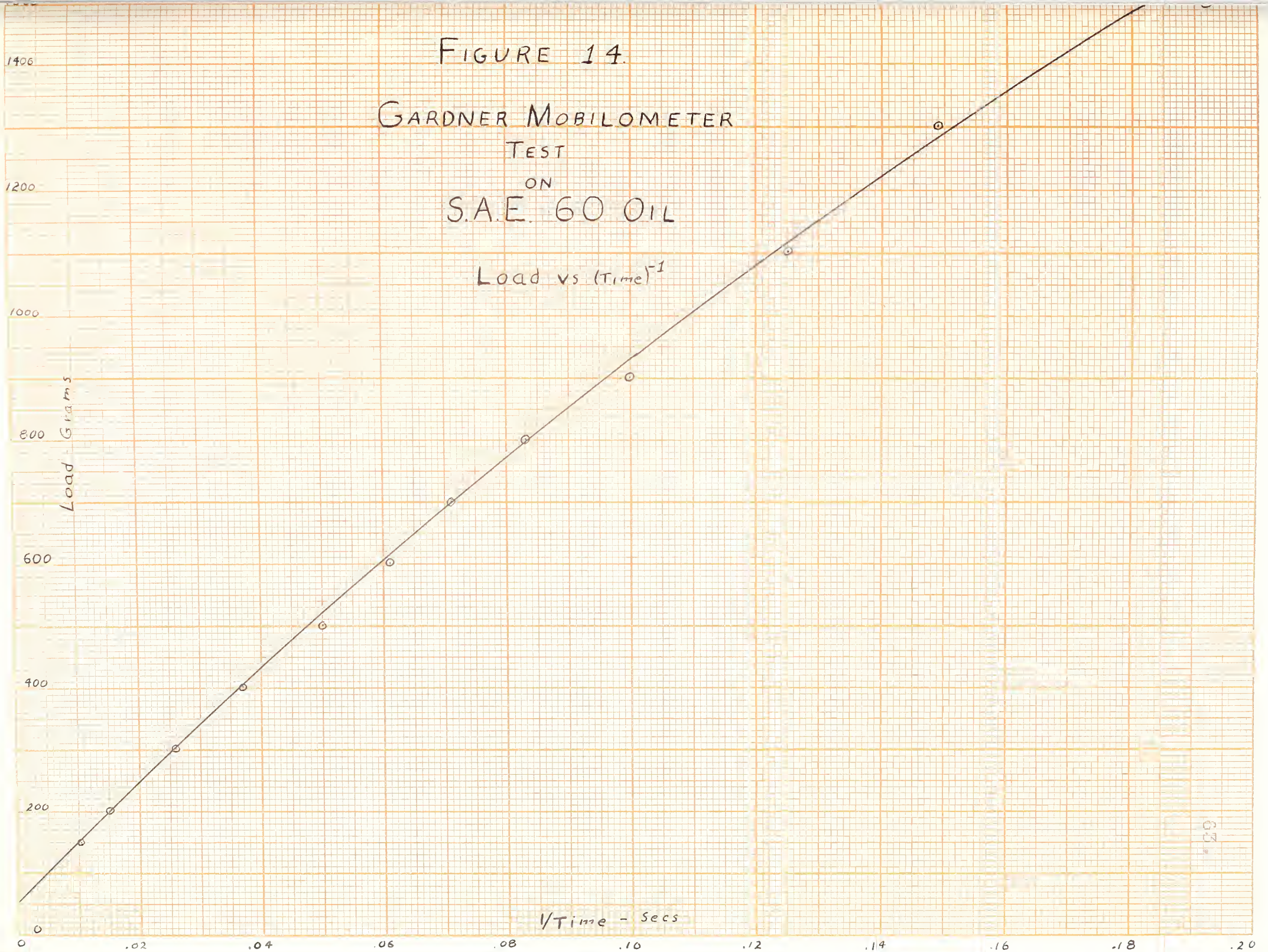
In confirmation of this phenomenon it has been reported (23) that in ball drop measurements with liquids usually assumed Newtonian (castor oil and U.S. Bureau of Standards' Sample P. 2), the graph of the logarithm of time versus logarithm of ball diameter has a slope of approximately -1.75 instead of -2 as would be predicted by Stoke's law.

Further and more certain evidence appears when the load-reciprocal of time relationship is extrapolated to zero as in Figure (14). This graph does not have a constant slope, indicating that the viscosity changes with rate of shear; it does not pass through the origin indicating that a finite load is required to move the plunger, that is, the oil has a definite yield value. It is quite possible that the temperature was below the pour-point of the oil, and that solid crystals were dispersed in the oil. Further, the exact composition of the oil is not known, and the presence of

FIGURE 14.

GARDNER MOBILOMETER TEST ON S.A.E. 60 OIL

Load vs $(\text{Time})^{-1}$



additives may result in such behaviour.

2. Gardner Slope and Rate of Change of Viscosity with Rate of Shear

The data obtained with the Gardner Mobilometer on gels Nos. 15-5, 273, and 12-2 are presented in Table V; and Table VI shows the viscosity-rate of shear data for these same gels. This is represented in Figures (15) and (16). For gel No. 15-5 the slope of the Gardner Mobilometer curve is -0.49, and the slope of the log-log plot of viscosity versus rate of shear is -0.50; for gel No. 273 the corresponding values are -0.43 and -0.45. This would seem to indicate that the Gardner slope is representative of the rate of change of viscosity with the rate of shear, within the limits of experimental error. A similar test was conducted on gel No. 12-2; this is represented in Figure (17). In this last case there is a definite break in the Gardner Mobilometer curve that is common in gels containing moderate amounts of peptizer. Two Gardner slopes may be calculated--the "1 second slope" and the "100 second slope". These have values of -0.29 and -0.64 respectively. The log-log plot of viscosity versus rate of shear has a slope of -0.64, indicating that the 100 second slope is representative of the viscosity rate of shear relationship.

The physical interpretation of this agreement is obscure. The Gardner Mobilometer curve may be represented as $d(\log F)/d(\log t) = k$, where F = force causing flow; t = time of fall; and k is a constant. The viscosity rate of shear

FIGURE 15

(a) GARDNER MOBILOMETER

Load vs Time

(b) CAPILLARY VISCOSIMETER

Viscosity vs Rate of Shear

GEL 15-5

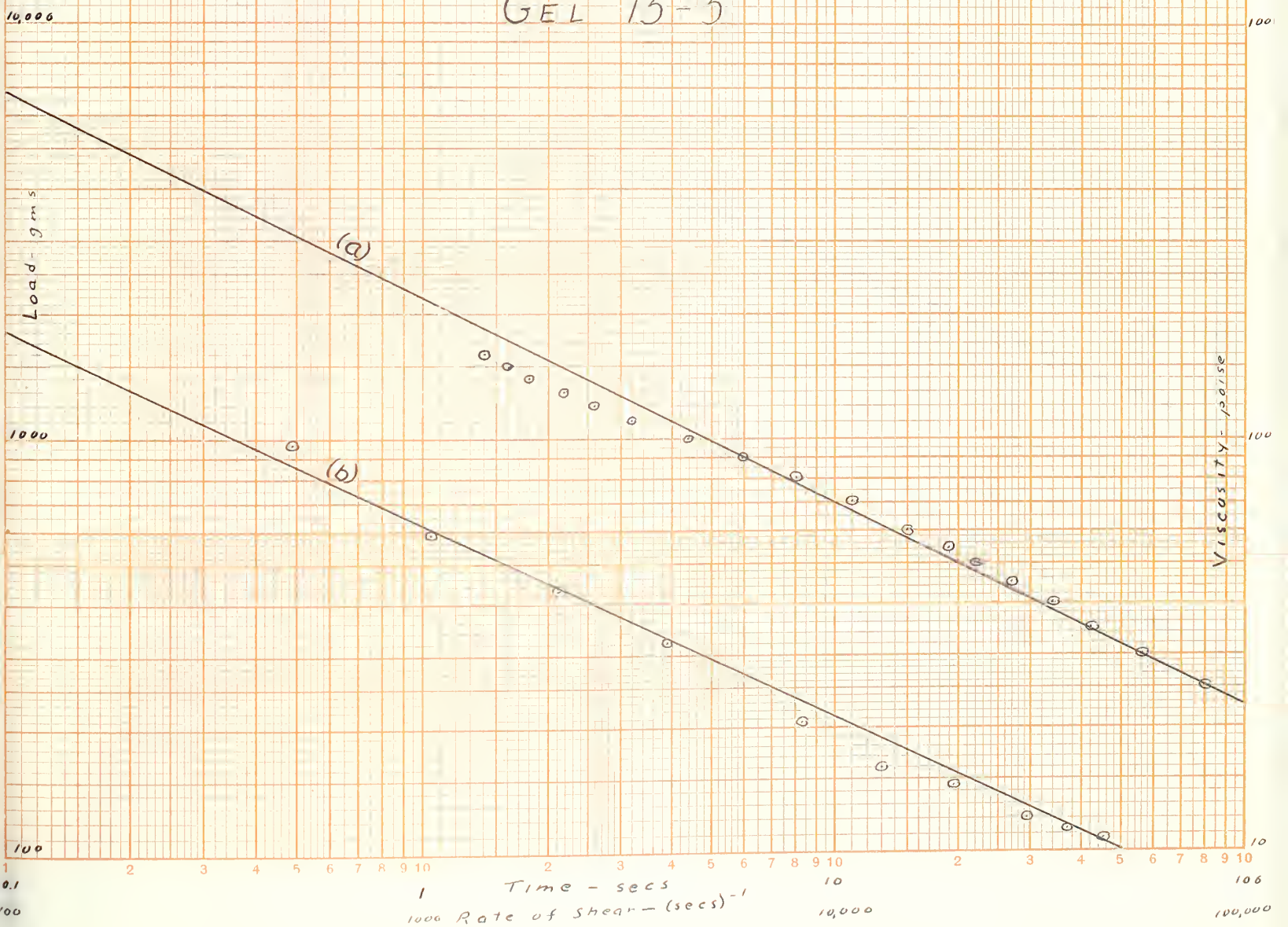


FIGURE 16

(a) GARDNER MOBILOMETER

Load vs Time.

(b) CAPILLARY VISCOSIMETER

Viscosity vs Rate of Shear

GEL 273

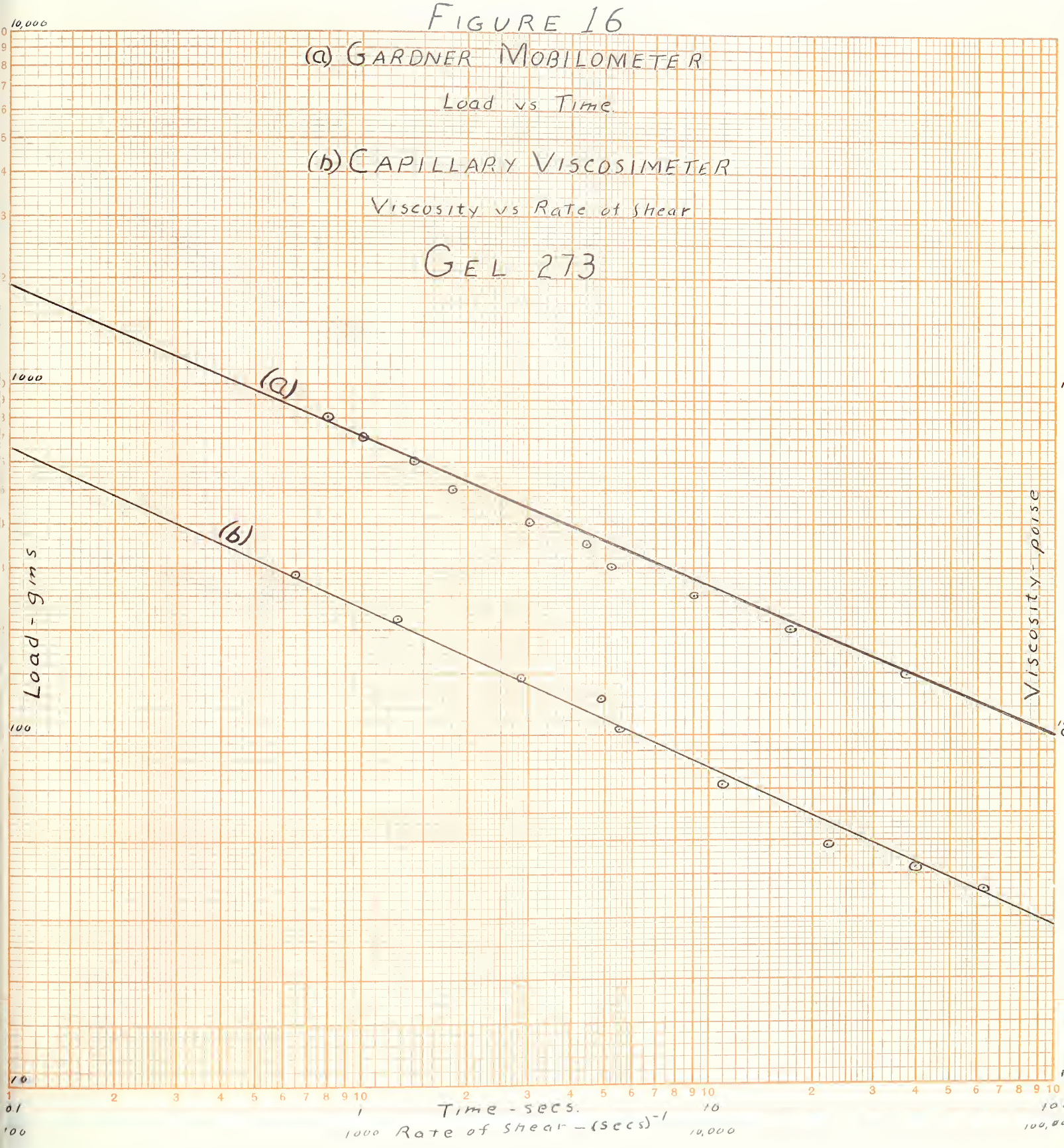
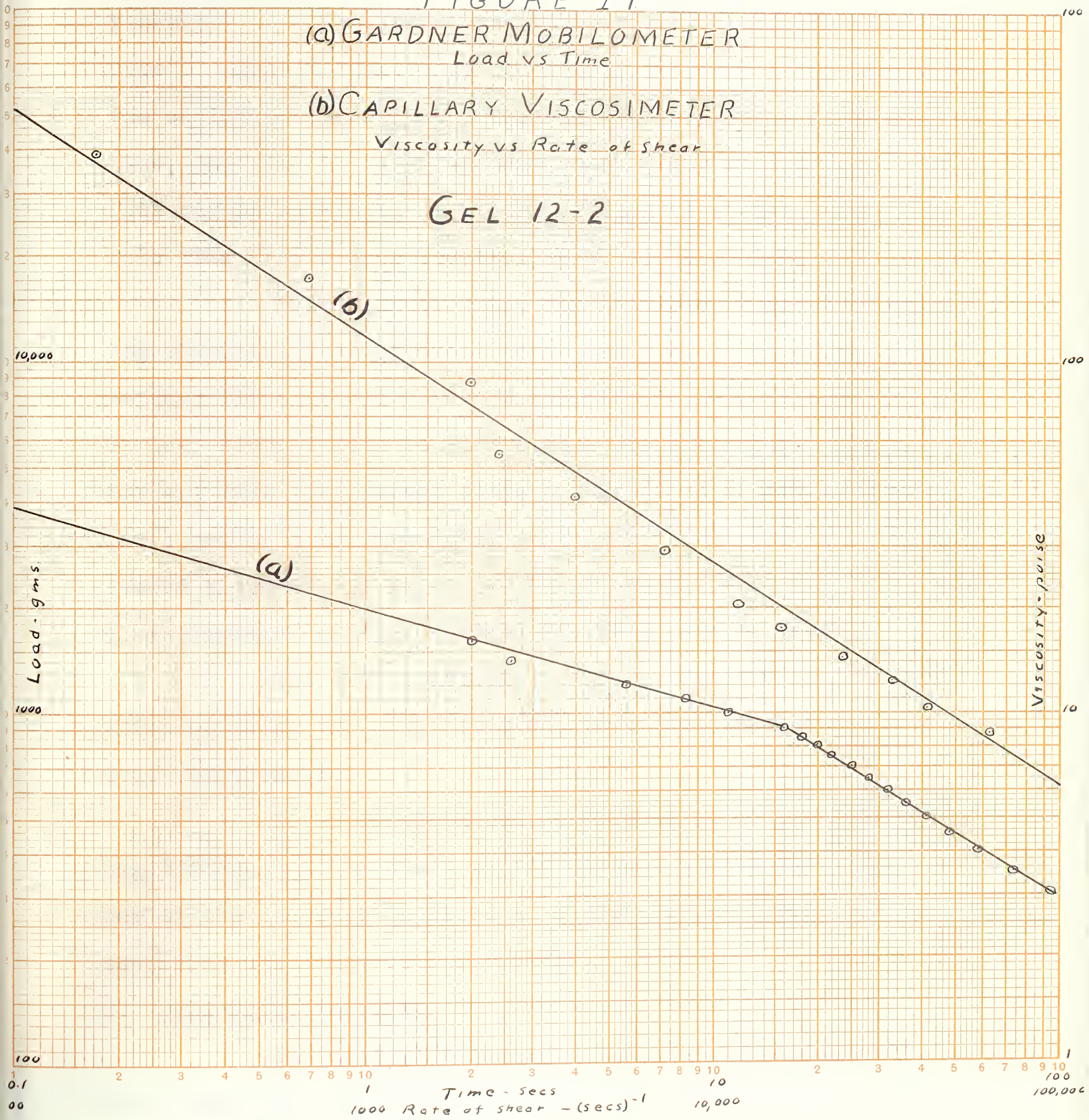


FIGURE 17


(a) GARDNER MOBILOMETER
Load vs Time
(b) CAPILLARY VISCOSIMETER
Viscosity vs Rate of Shear
GEL 12-2
(b)
(a)
Load - gms
Viscosity - poise
Time - secs
1000 Rate of shear - (secs)⁻¹
10,000
1000
100
100
10
1
0.1
00
1
2
3
4
5
6
7
8
9
10
100
10,000
100,000

curve may be represented as $d(\log \eta)/d(\log R_S) = K$, where η is the viscosity, R_S is the rate of shear, and K is a constant. Viscosity has the dimensions (force.time)/(length)^2, and rate of shear 1/time, thus $d(\log(\frac{Ft}{L^2}))/d(\log \frac{1}{t}) = K_1$. Since in the capillary viscometer the only variables are force and time; that is, L^2 is a constant, then $d(\log Ft)/-d(\log t) = K$. This may be rewritten as $d(\log F)/d(\log t) = -1-K$. Equating this with the Gardner equation we obtain $k = -1-K$.

According to this, for gel 15-5, since the log-log viscosity rate of shear curve has a slope of -0.50, the Gardner slope should be -0.50 (compare -0.49); for gel 275 the Gardner slope should be $-1 + 0.45 = -0.55$ (compare -0.43). For gel 18-2 the Gardner slope should be $-1 + 0.64 = -0.36$; the 1 second slope is -0.79. This would indicate that the 1 second slope rather than the 100 second slope is representative of the rate of change of viscosity with rate of shear.

The data available is not sufficient to indicate which of these two possibilities, if either, represents the true relationship.

No explanation can be offered as to the physical significance of the break in the Gardner viscometer curve, nor to the decrease in slope at higher rates of fall. The peptizing agent may be responsible.

3. Ball Drop Viscosity

In Table VIII is given the ball drop viscosity data for a gel containing 9% solids and 1.35% xylenol. The

test was carried out on three samples of the same gel. The deviation from the average value is never greater than 6%; this indicates that the gel was reasonably homogeneous. Since no precautions were taken to centre the ball in the cylinder and no effort was made to avoid parallax, part of this deviation may be due to experimental error. This agreement may be contrasted with the data on the gels prepared at Suffield given in Table X. Agreement between different ball sizes is also good once the Ladenburg correction is applied. Using balls varying in size from 7/16 of an inch to 1/8 inch in diameter, the average deviation is 3.8%.

In working with thinner gels the larger diameter balls often gave values of viscosity that were lower than the values obtained with the smaller balls. Data for two such cases is given in Tables VIIb and VIIc. In the first case the viscosity value increases as the ball diameter decreases from 5/16 to 1/8 inch, and then becomes constant. In the second case the value increases as the ball diameter decreases from 7/16 to 1/16 inch.

This agrees with the work of Mesin and Mahling (45) who found that correct values for the initial viscosity of P.M.M.A. gels was obtained only when a definite ratio of rate of fall to ball diameter was not exceeded.

4. Healing Time

Table VIII presents the healing time data for a gel containing 15% Aspalun and 5% xylenol. All runs with a particular gel were made under duplicate conditions, that is,

pressure, time of efflux, etc., as far as this was possible. According to Knudsen and Bereda (20) the value of ΔT/VD is a constant for any gel at a definite temperature and independent of pressure, efflux velocity, capillary diameter, etc. The main difficulty encountered was the indistinct outline of the jet pattern because of jet vibrations. This was particularly true with the thicker gels. However, by taking the average of from four to eight photographs, it is believed that a fairly accurate value of ΔT/VD was obtained.

5. Napalm Gels

The laboratory data and range data for 7, 9, and 12% Napalm gels are given in Table III. These, together with the data of Knudsen and Bereda (20), are represented graphically in Figure (18) to give the complete range for Napalm gels. The nozzle used was 1/8 inch diameter and the elevation 20°. The features of these curves worthy of notice are:

1. For higher slopes of ΔT/VD (thin gels) the range increases with decreasing slope.

2. A transition region over which the range is practically constant as the slope decreases.

3. At lower slopes of ΔT/VD the range decreases at an increasing rate as the slope decreases.

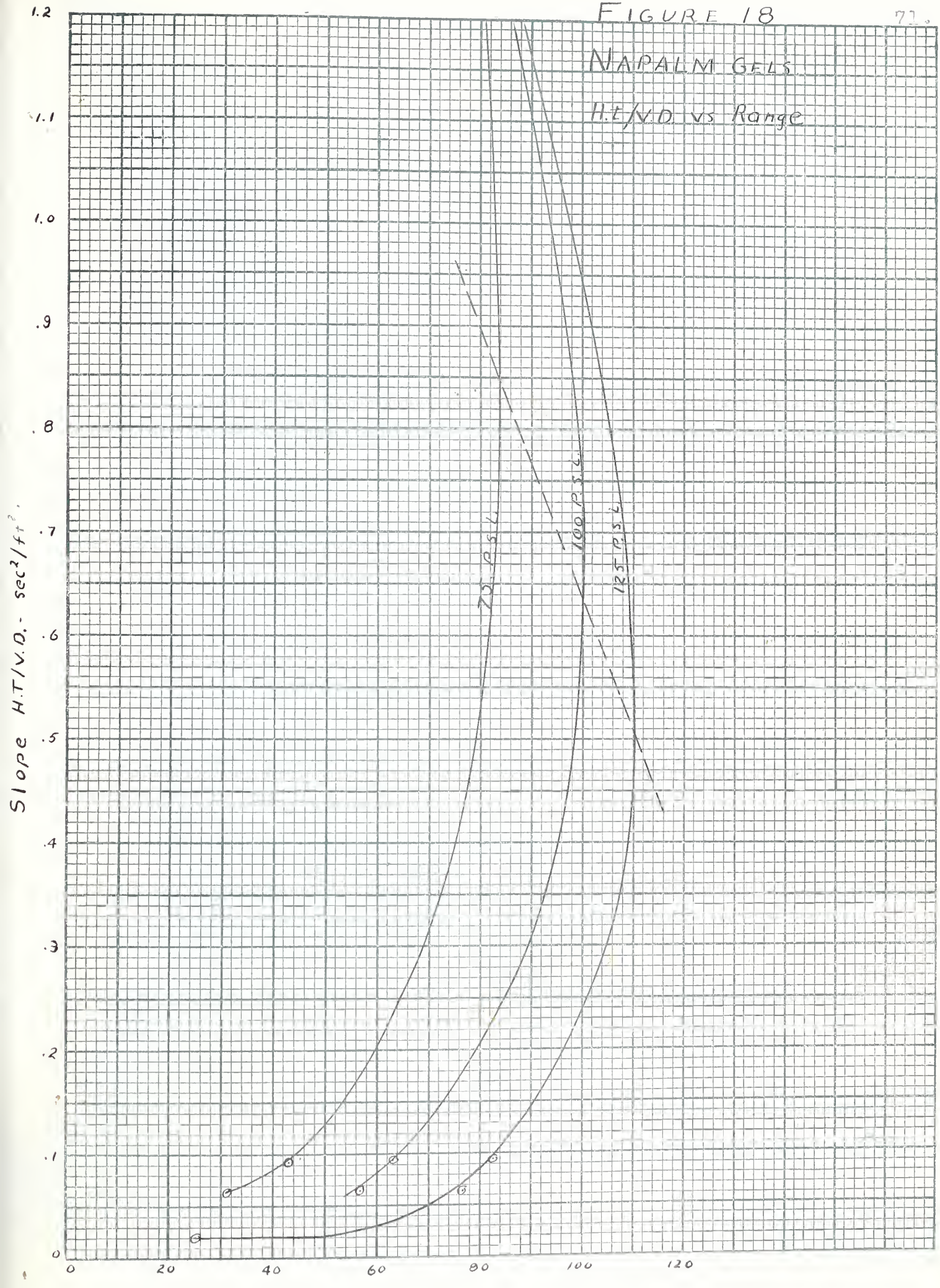
4. A line joining the points of maximum range on the curves is a straight line.

We might expect that for flame throwers using higher pressures the maximum range would be obtained using gels of the lower ΔT/VD slopes, that is, higher Napalm concentrations

FIGURE 18

NAPALM GELS

H.t/V.D. vs Range



6. Field Data

A series of eight napalm fuels varying in soap concentration from 3.25 to 7.5% was prepared at Duffield and fired in a Mark IK. II flame thrower. The complete set of laboratory data and field performances is given in Table X. The A nozzle has an area of 0.78 square inches, the B nozzle 0.45 square inches.

Figure (19) shows the maximum effective range (M.E.R.) of the fuels plotted against HT/VD for two different nozzles and at two elevations, and Figure (20) shows these four curves plotted on the same axis. These curves are of the same general shape as those obtained with the experimental flame thrower, showing regions of increasing range, constant range, and decreasing range as the slope HT/VD is decreased. These curves all show a maximum range for gels containing from 5% to 6% napalm. The range apparently is not greatly affected by the nozzle area, but is much more sensitive to elevation of firing.

In Figure (21) the M.E.R. is plotted against the 100 second Herschel consistency. These curves are similar to those in Figure (19).

Figure (22) shows the variation in jet length with HT/VD. A 4.5% gel with an M.E.R. of 130 yards has a jet length of 50 yards; the fuel travels 70 yards after the jet has been broken. A 7.5% gel with an M.E.R. of 125 yards had a jet length of 110 yards; the jet was unbroken over almost the whole course of flight.

FIGURE 19

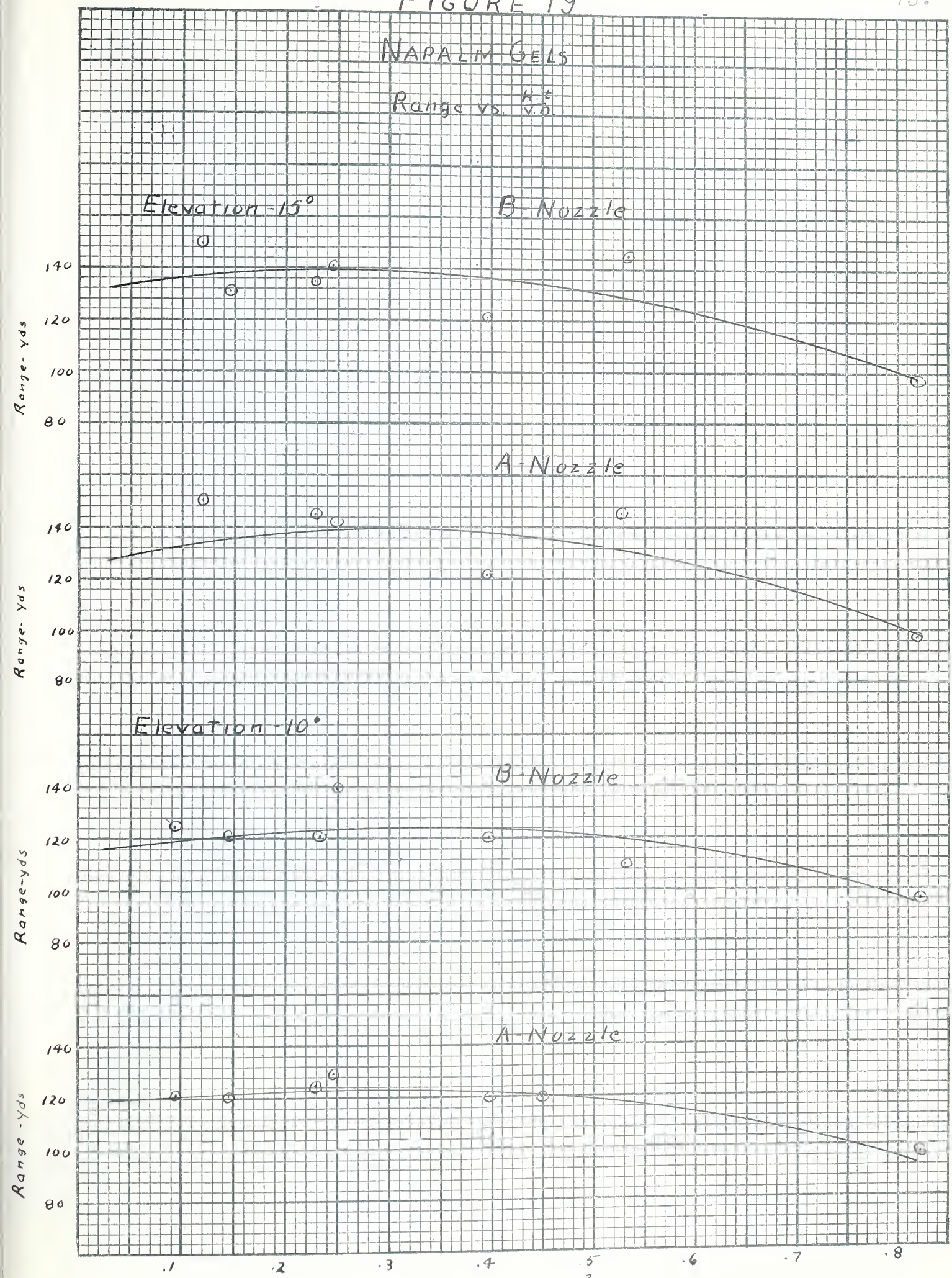

NAPALM GELS
Range vs. H.T/V.D
Elevation - 15°
B Nozzle
A-Nozzle
Elevation - 10°
B-Nozzle
A-Nozzle
Range - yds
140
120
100
80
.1
.2
.3
.4
.5
.6
.7
.8
Slope H.T./V.D - sec²/ft²

FIGURE 20

NAPALM GELS

Range vs H.T./V.O.

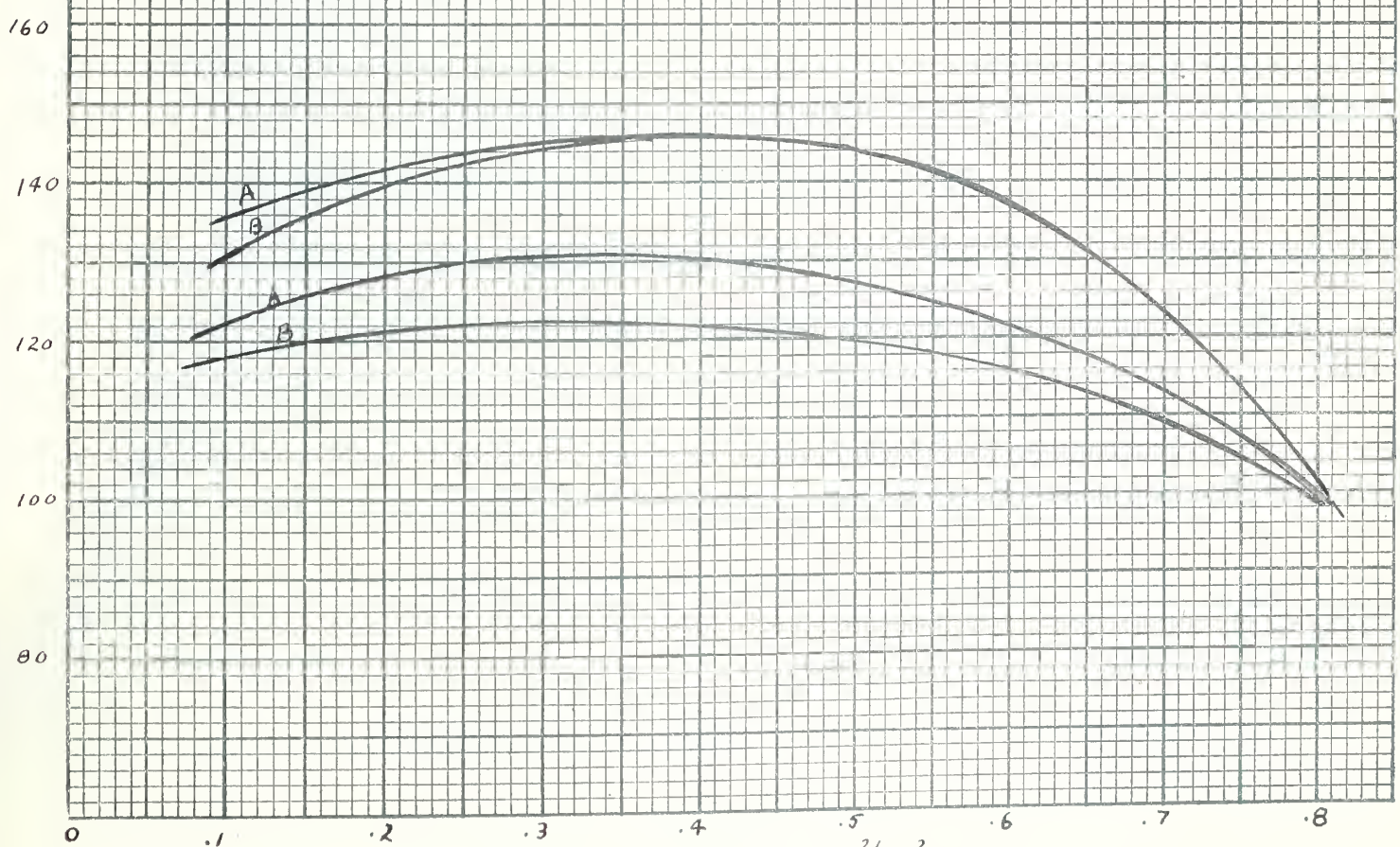


Figure (23) is a plot of M.E.R. minus the jet length, that is, the distance traversed after the jet broke, versus HT/VD. This curve is almost level for gels below 5-1/2% Napalm but falls off rapidly for more concentrated gels. For a given fuel the jet length should be independent of the elevation of firing. However, the M.E.R. should increase to a maximum as the firing elevation is increased. Under the given firing conditions apparently the maximum distance from jet breakup to M.E.R. is about 70 yards when the elevation is an optimum. This would indicate that the elevations used were an optimum for gels below 5-1/2% Napalm, but that this is too low for the gels of higher concentrations, and that the M.E.R. for these gels would be increased if the angle of elevation of firing is increased. A correct comparison is not obtained from the M.E.R. of the gels when they are both fired at the same elevation unless the gels are very similar.

Figure (24) represents the relationship of HT/VD and Napalm concentration. The data for this is taken from Knudsen and Bereda (30), Table II and Table X. Over the major portion of this curve, up to 8% Napalm, the relationship is linear and from there curves upwards. The agreement is fairly good in most cases. The discrepancies may be due to Napalm grade, or ageing, or effect of storage. It seems, however, that HT/VD is an exponential function of the soap concentration.

Figure (25) is a plot of 100 second Gardner

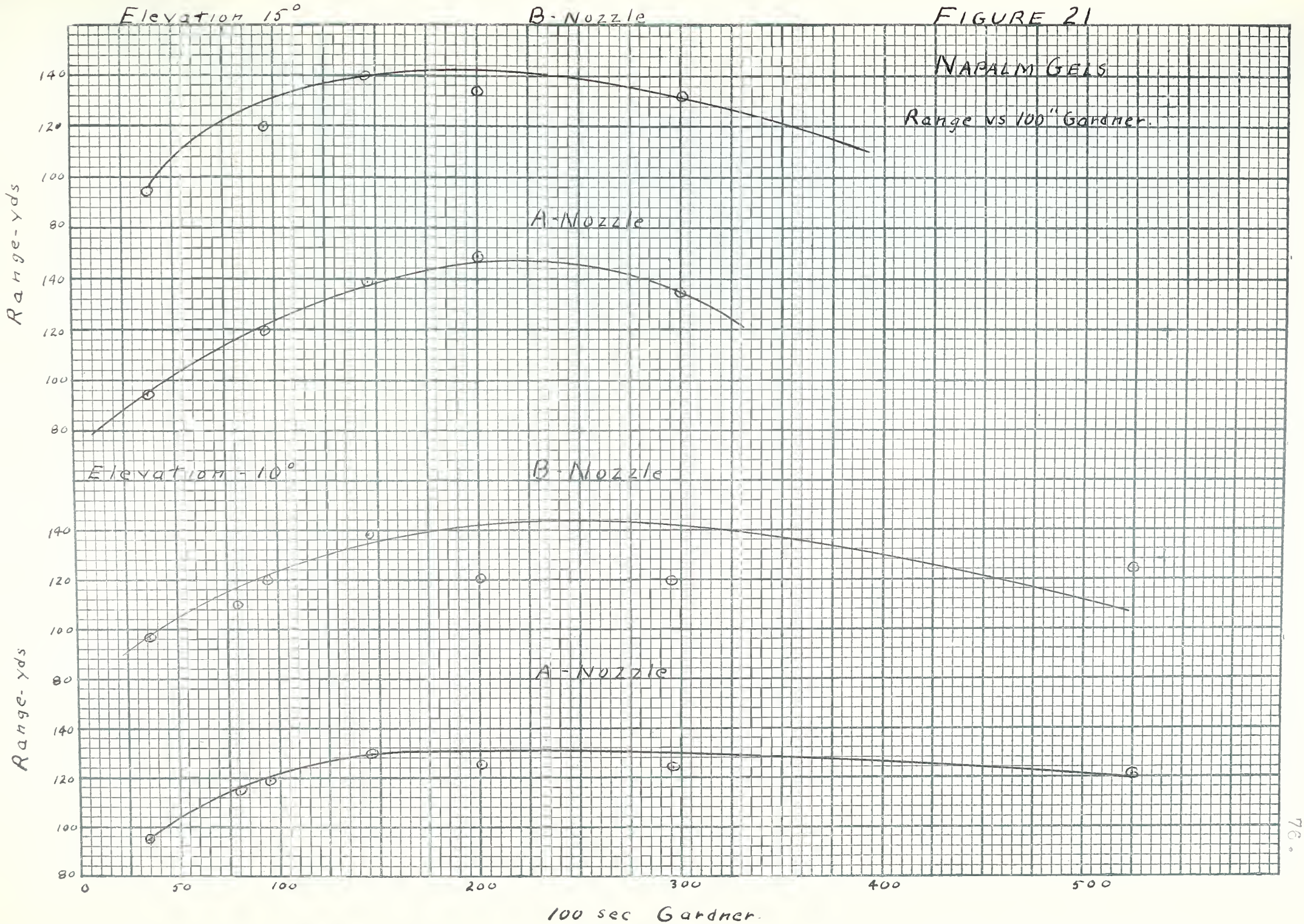


FIGURE 21

NAPALM GELS

Range vs 100" Gardner.

FIGURE 22

NAPALM GELS

Jet Length vs. $\frac{H.T.}{V.D.}$

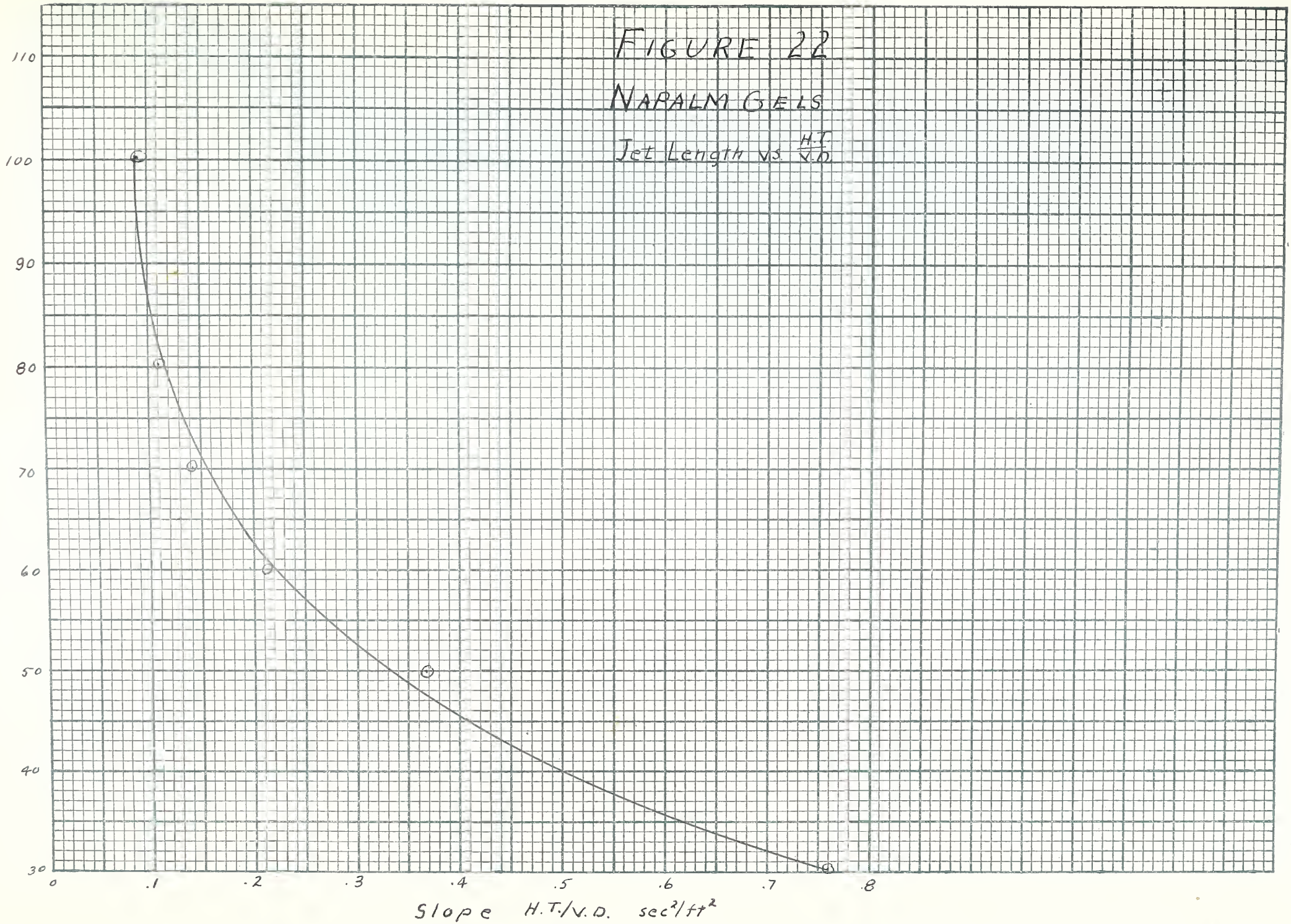
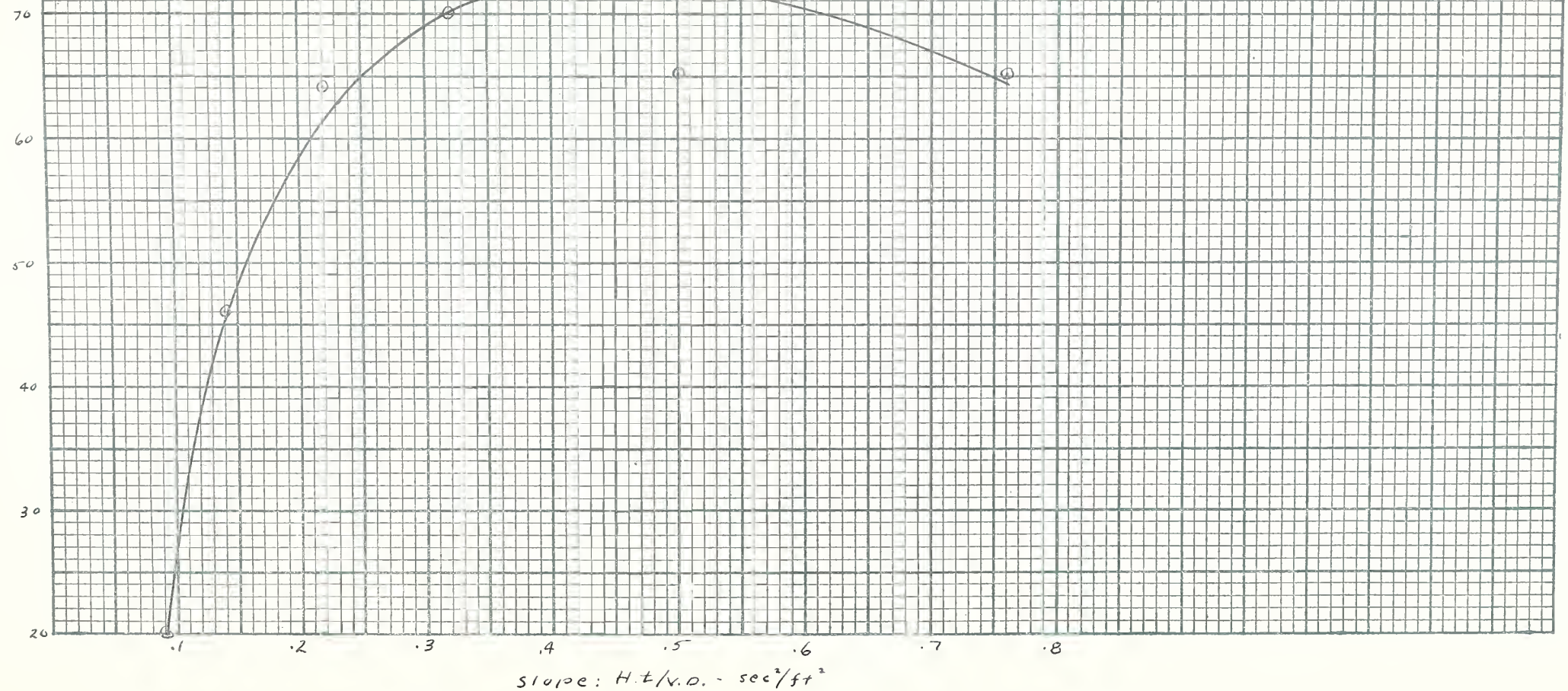


FIGURE 23

NAPALM GELS

Distance - Jet-End to M.E.R. vs. H.T./V.D



against the Napalm concentration on semi-log paper. The relationship here is more complex than that of HT/VD versus Napalm concentration.

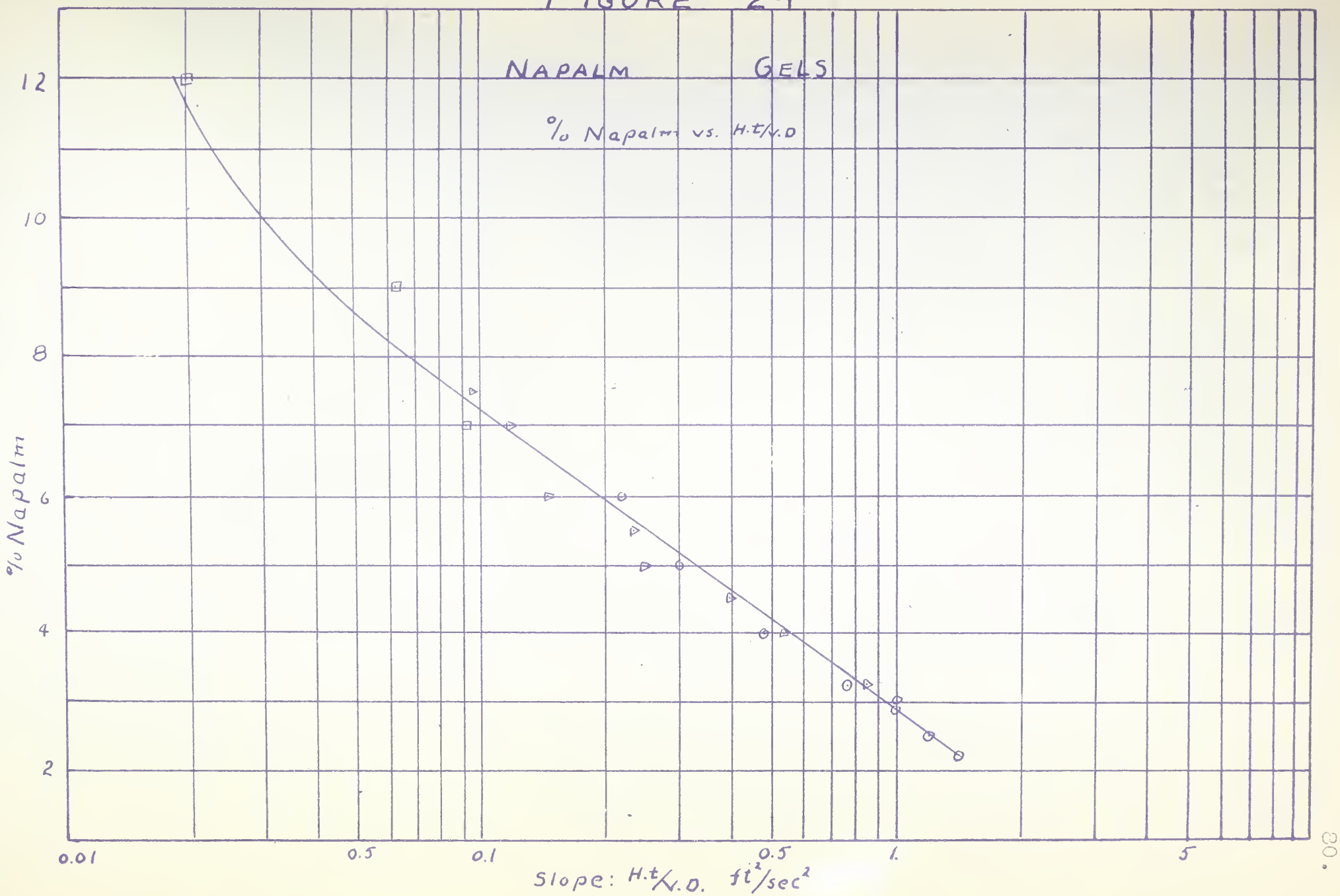
Figures (26) and (27) represent the variation of 100 second Gardner consistency with HT/VD. From these curves it can be concluded that if it were possible to predict the field performance of straight Napalm fuels by measurements of HT/VD, it could also be predicted from Gardner consistency. With gels of low concentration, say 5.5%, the HT/VD is much more sensitive to changes in Napalm concentration than is the Gardner consistency; at higher concentrations, however, the reverse is true. Thus, for straight Napalm gels the Gardner consistencies may be a more reliable method for predicting the field performance, and for lower concentrations the HT/VD relationship may be more useful.

7. Napalm gels napthized with Xylenol

The data for Napalm gels containing xylenol is presented in Table XI. By referring to Figure (18) we can predict the range of these gels from the performance of straight Napalm gels with similar heating times. A comparison of actual and predicted field performance is shown in Table XIII. This is represented graphically in Figures (28) and (29).

For the most part the agreement is good considering the magnitude of possible experimental error. Although the effect of wind was reduced as much as possible, this can-

FIGURE 24


NAPALM GELS
% Napalm vs. H.t/N.D
% Napalm
12
10
8
6
4
2
0.01
0.5
0.1
0.5
1.
5
Slope: H.t/N.D. ft²/sec²

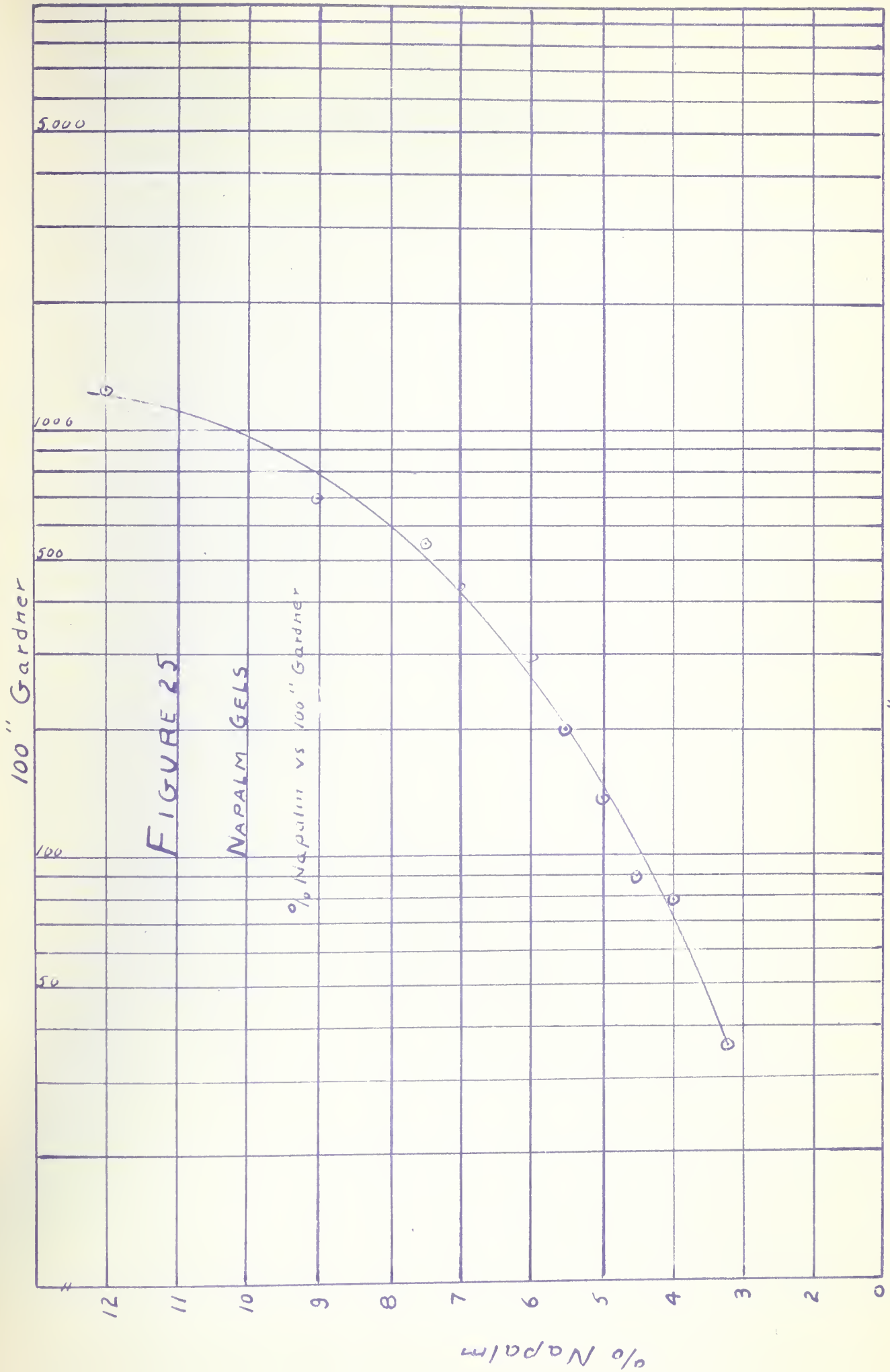


FIGURE 25

NAPALM GELS

% Napalm vs 100" Gardner

FIGURE 26

NAPALM GELS

100" Gardner vs H.T./V.D.

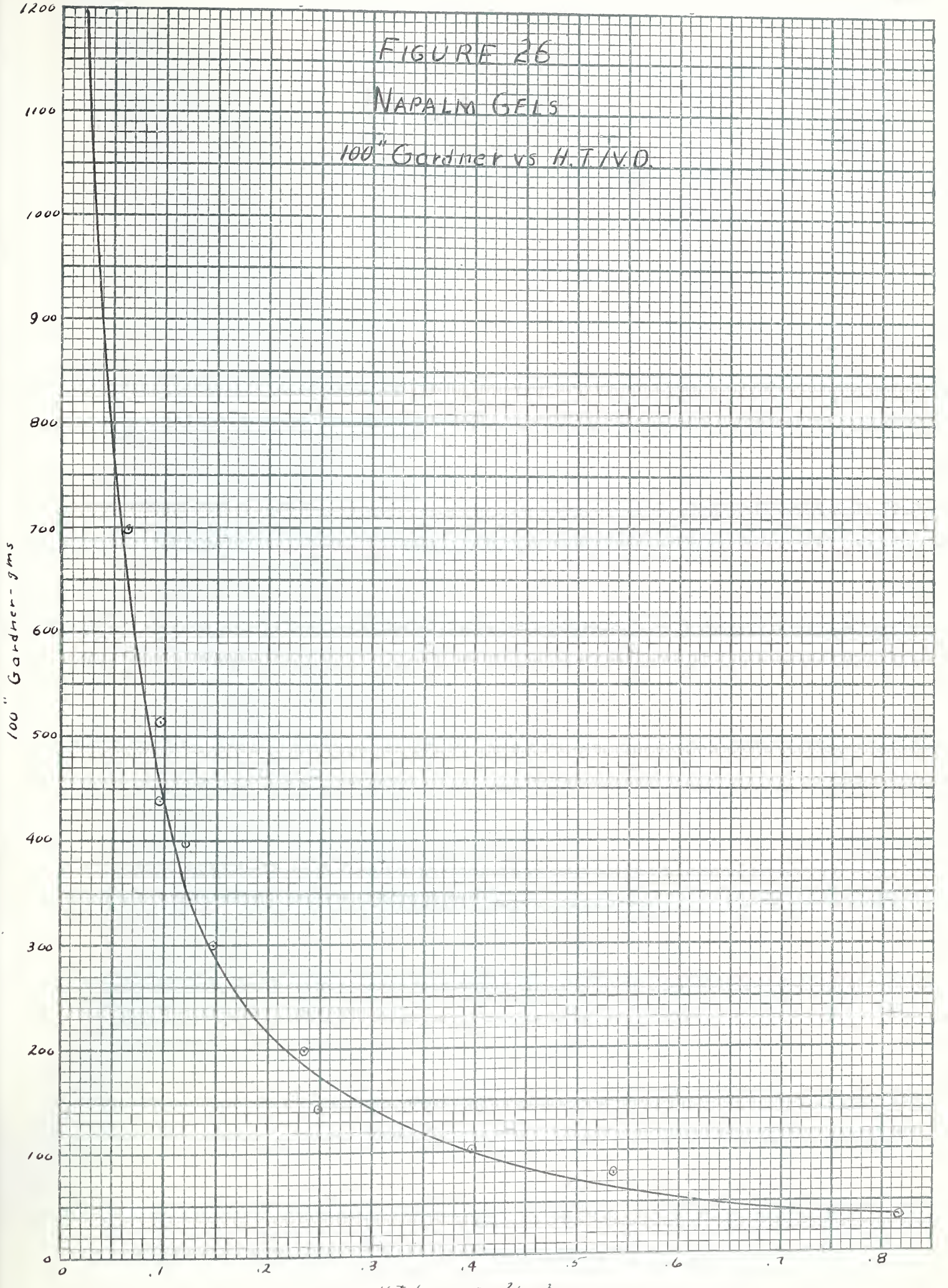


FIGURE 27

NAPALM GELS

100" Gardner vs Ht/V.D.

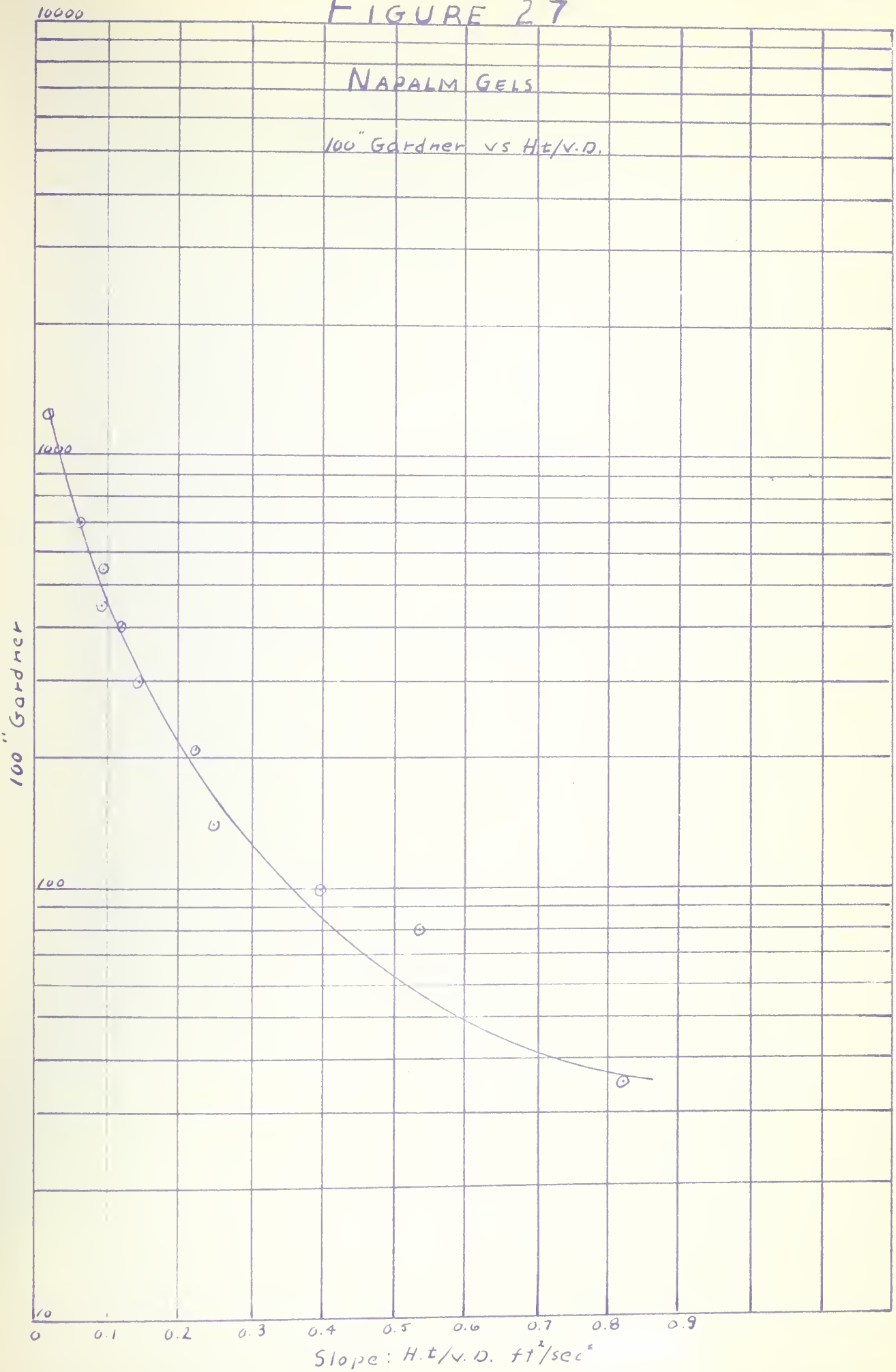


TABLE XIII

% Xylenol	HF/VD	RANGE 75 p.s.i. Act.	75 p.s.i. Predict.	75 p.s.i. Diff.	RANGE 100 p.s.i. Act.	100 p.s.i. Predict.	100 p.s.i. Diff.	RANGE 125 p.s.i. Act.	125 p.s.i. Predict.	125 p.s.i. Diff.
7% Napalm										
0.25	0.153	80	75	+5	75	75	+2	83	91	-8
0.50	0.187	65	61	+4	95	81	+12	98	98	0
1.10	0.227	59	64	-5	82	83	- 1	--	100	--
1.5	0.281	66	68	-2	81	89	- 8	98	105	-7
9% Napalm										
0.5	0.0581	56	50	+6	65	55	+10	--	--	--
0.75	0.0739	59	56	+3	61	59	+ 2	--	--	--
1.0	0.096	45	43	+2	67	63	+ 4	86	93	-7
1.5	0.094	42	43	-1	65	63	0	--	--	--
2.0	0.128	56	51	+5	85	70	+13	98	88	+10
12% Napalm										
1	0.0228	--	--	--	46	--	--	64	58	+6
2	0.039	30	26	+4	63	48	+15	70	70	0
3	0.0445	--	--	--	59	51	+8	78	70	+8
5	0.095	56	43	+13	76	63	+13	--	--	--
15% Napalm										
1	0.203	--	--	--	--	--	--	55	55	0
3	0.233	--	--	--	--	--	--	40	40	0
5	0.0302	--	--	--	31	32	-1	56	56	0
9	0.037	40	30	+10	60	50	+10	80	67	+13

FIGURE 28

XYLENOL PEPTIZED GELS

Range vs H.T./V.D.

△ 7% Napalm, 75 P.S.I.
□ 7% Napalm, 100 P.S.I.
⊙ 7% Napalm, 125 P.S.I.
+ 9% Napalm, 75 P.S.I.
× 9% Napalm, 100 P.S.I.
⊗ 9% Napalm, 125 P.S.I.

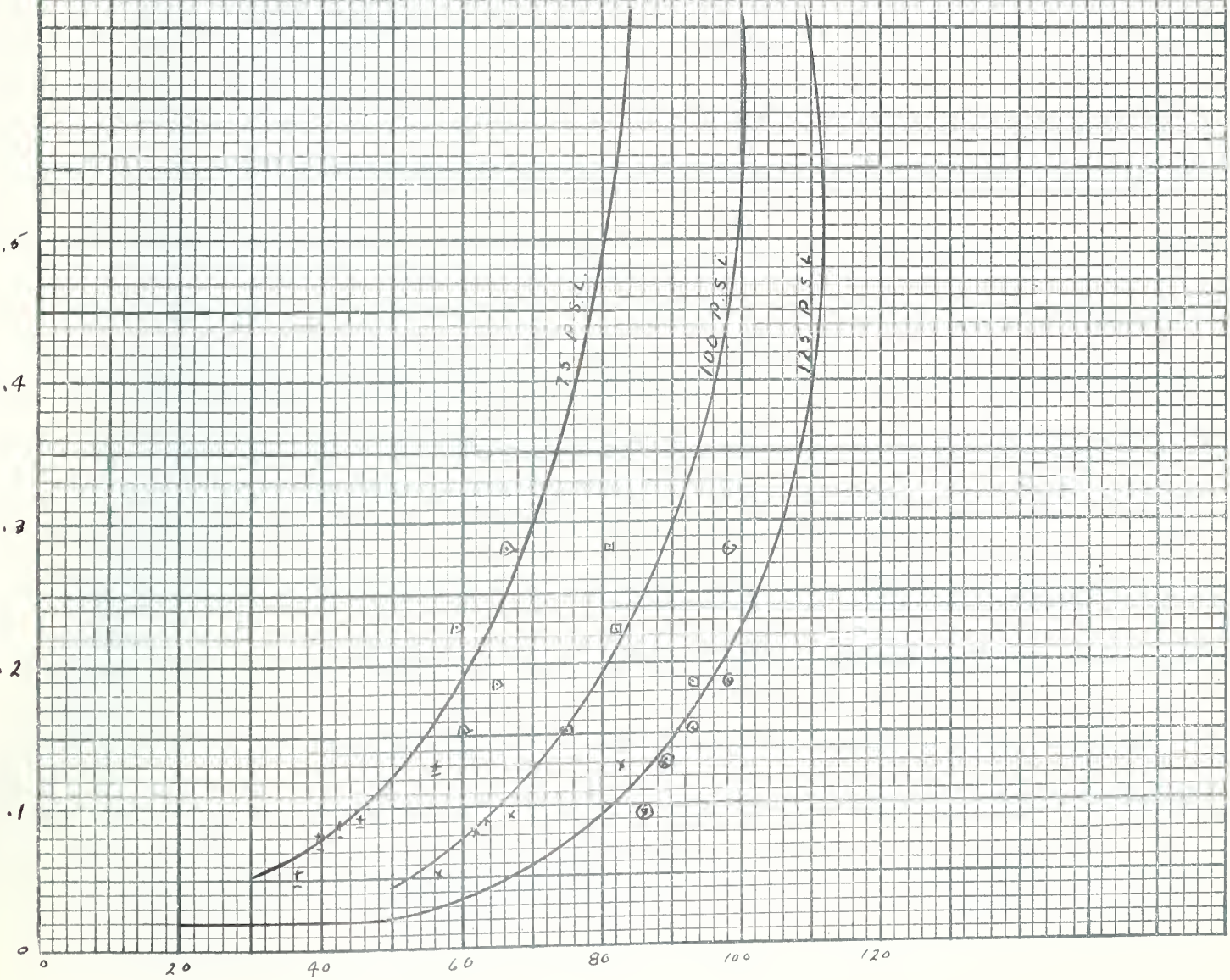
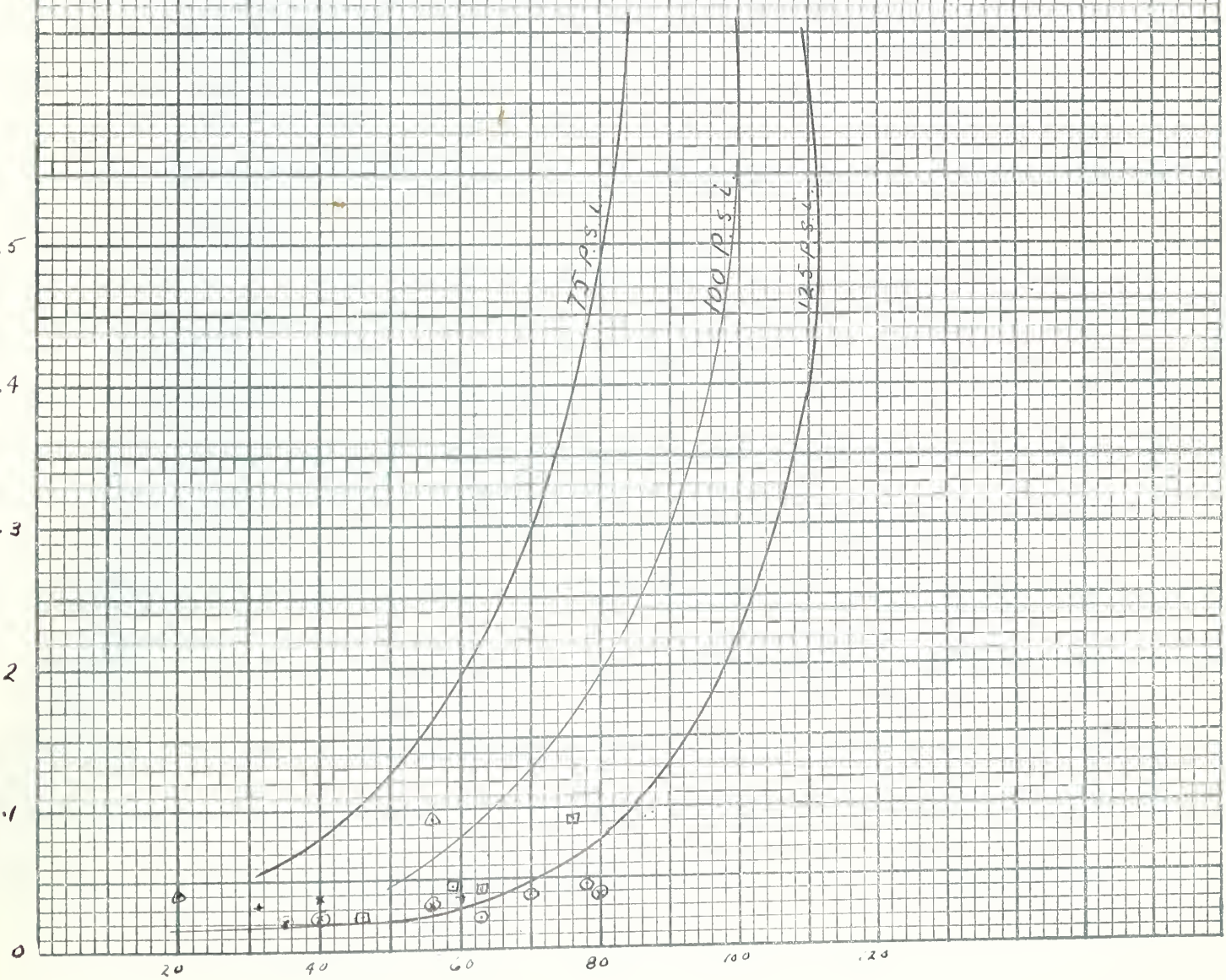


FIGURE 29

XYLENOL PEPTIZED GELS

Range vs H.T./V.O.

△ 12 % Napalm, 75 P.S.I.
□ 12 % Napalm, 100 P.S.I.
○ 12 % Napalm, 125 P.S.I.
× 15 % Napalm, 75 P.S.I.
+ 15 % Napalm, 100 P.S.I.
⊗ 15 % Napalm, 125 P.S.I.



not be totally disregarded, and may account for some of the variations. Other variables that could not be controlled are

1. Air temperature - it is unknown how this affects the range.
2. Angle of Elevation - the flame thrower stand was set up in snow or gravel, and the elevation may have varied by 1 or 2°. This would undoubtedly have a marked effect on the range.
3. Napalm grade - Napalm is not a reproducible mixture and varies somewhat in behavior.

The correlation between Gardner consistency and range obtained for straight napalm gels does not hold with gels using xylenol as a peptizer. As illustrated in Figure (30) the range is independent of the Gardner consistency. Further, no correlation is possible between initial viscosity and range.

The logarithm of viscosity versus the percent xylenol for gels containing 7, 9, 12, 15% Napalm is plotted in Figure (31). These curves would seem to indicate that as the xylenol content is increased the viscosity decreases at a decreasing rate, and ultimately would reach a constant value. There is insufficient data available to predict what this minimum viscosity will be. This is in agreement with the behavior of water peptized gels which also reach a minimum consistency that is independent of the water content after a definite value has been exceeded (36).

Figure (32) indicates that for gels with high

FIGURE 30

XYLENOL PEPTIZED GELS

Range vs 100' Gardner.

Pressure: 1000 P.S.I.

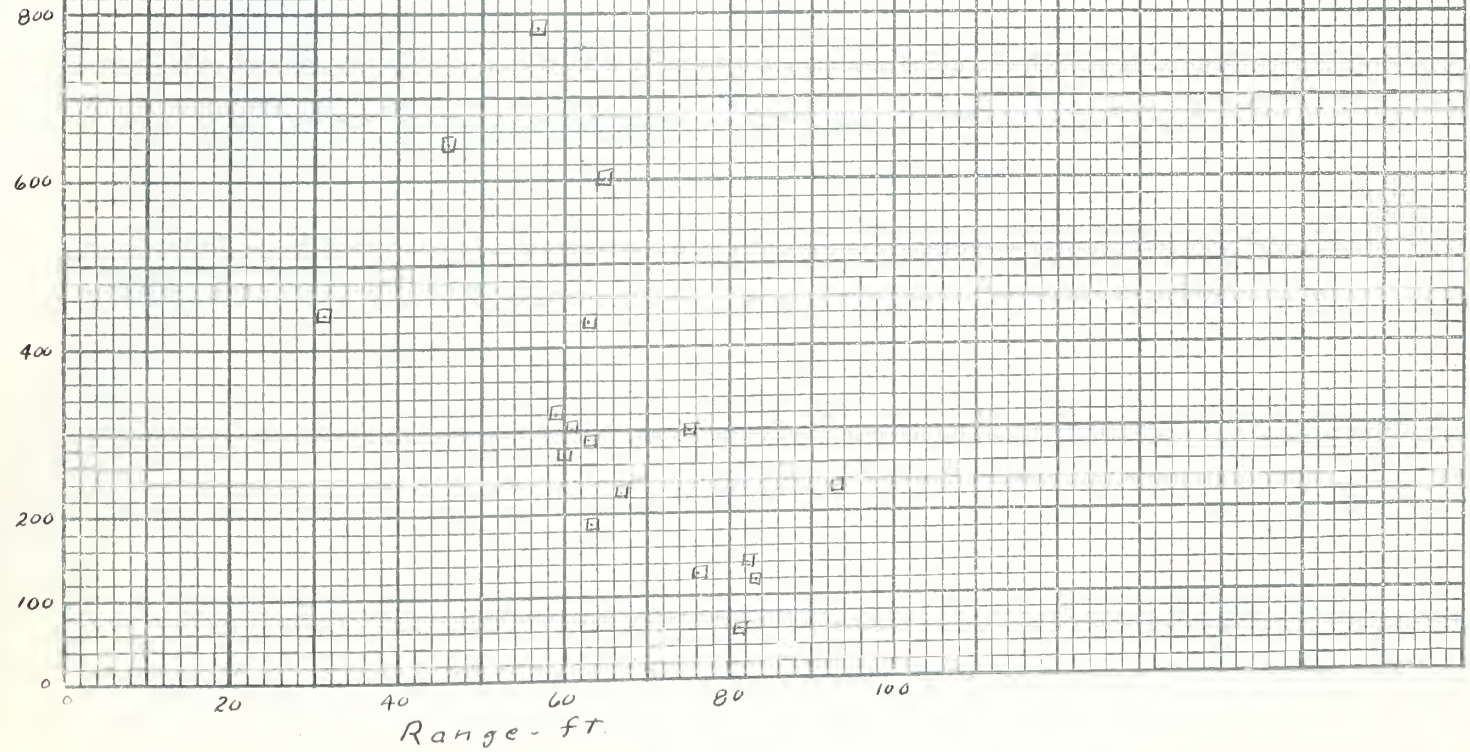


FIGURE 31

XYLENOL PEPTIZED GELS

Viscosity vs % Xylenol

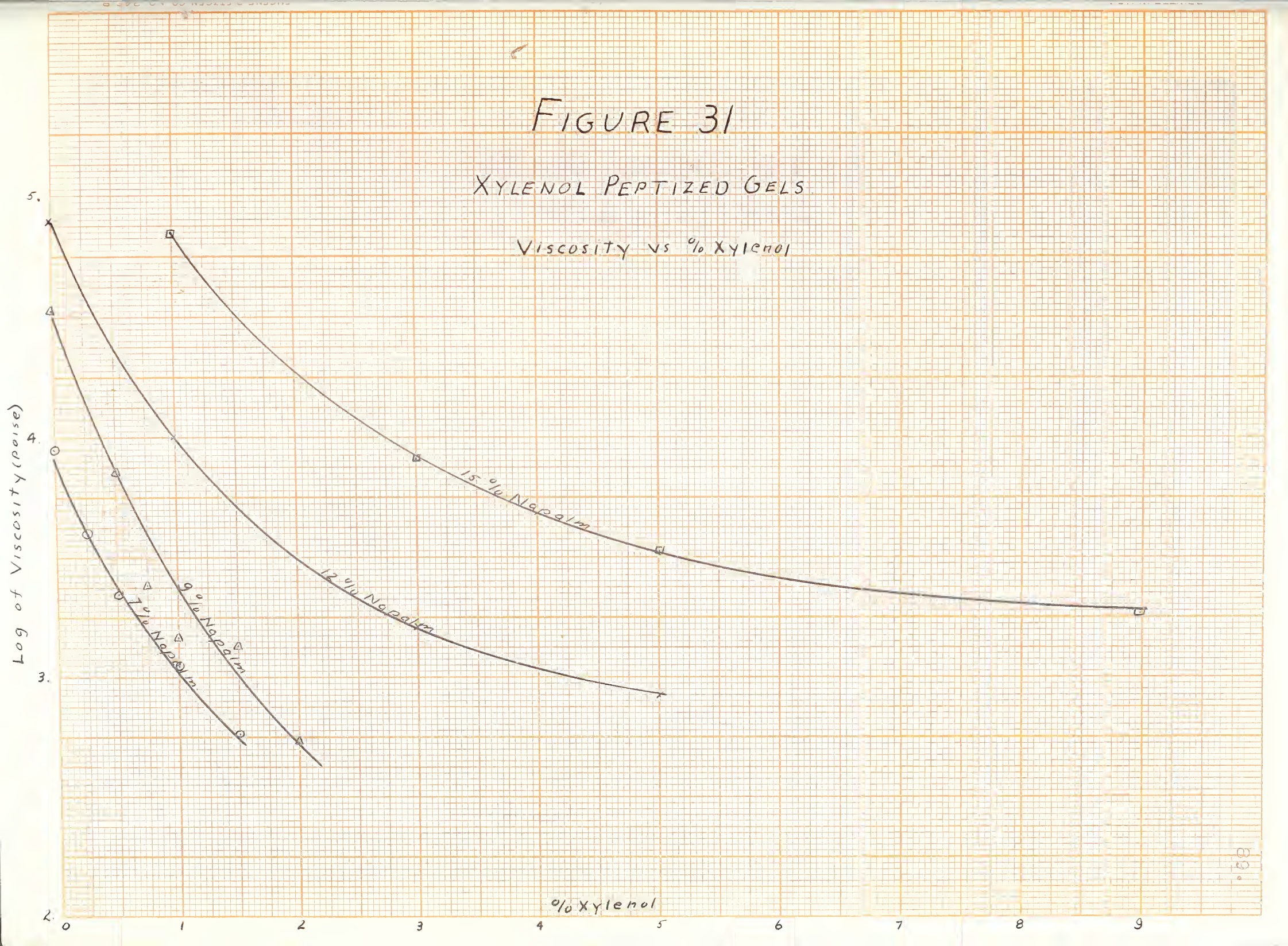
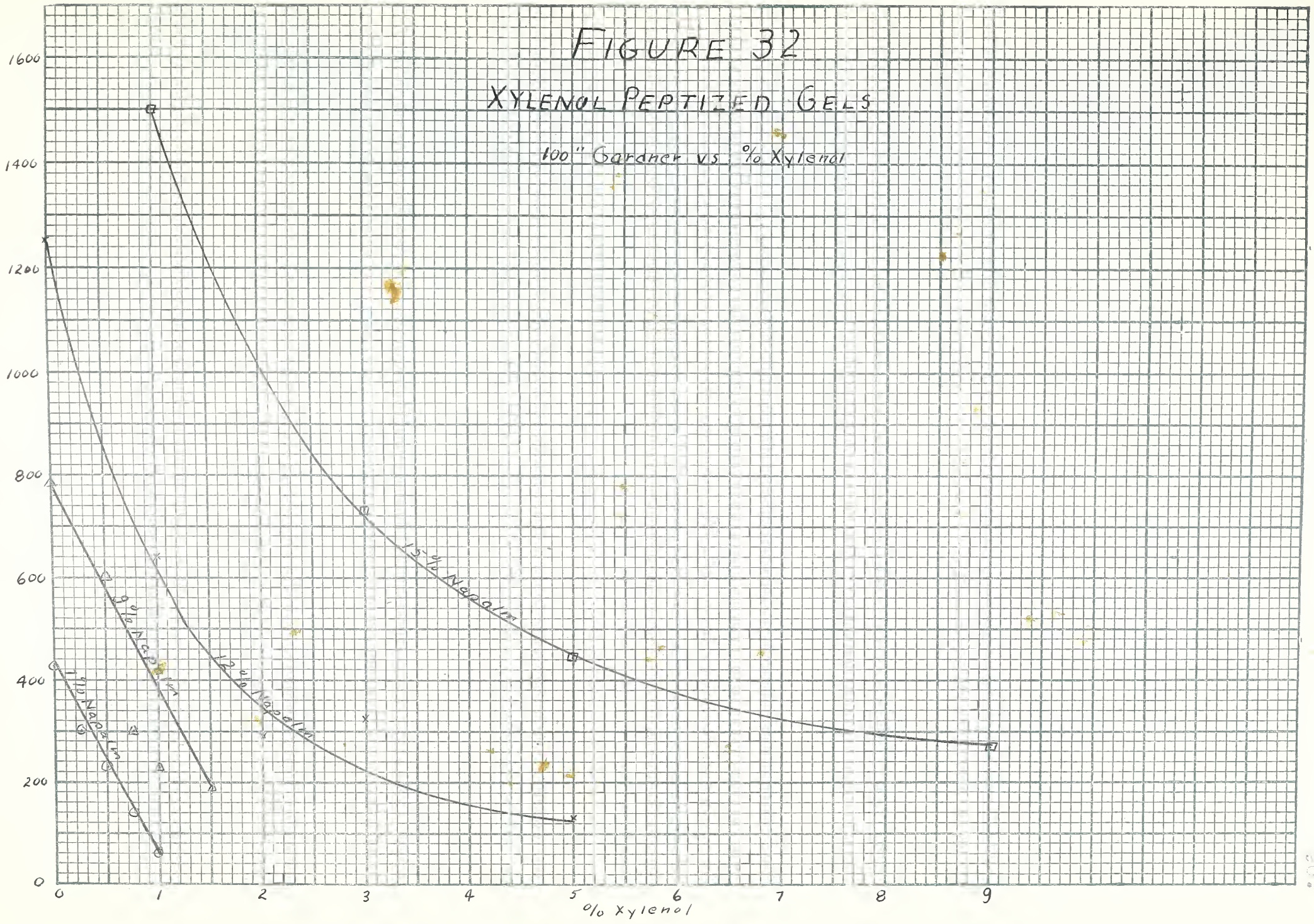


FIGURE 32

XYLENOL PEPTIZED GELS

100" Gardner vs. % Xylenol



Napalm content at least, a minimum Gardner consistency is reached as the fraction of xylenol is increased.

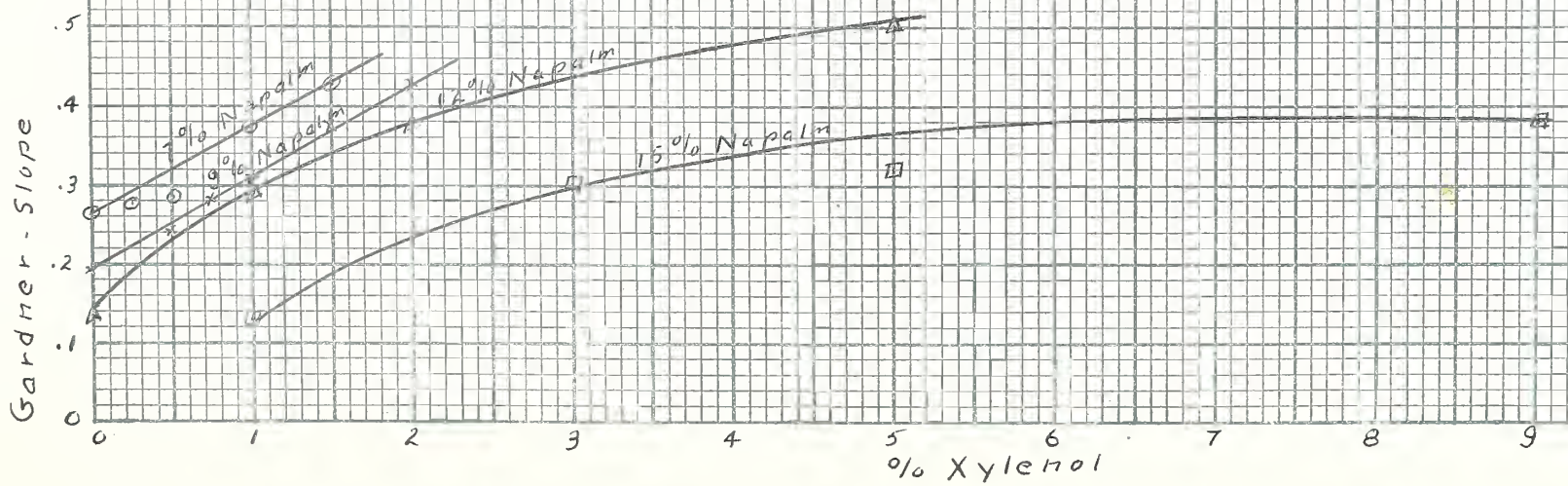
A gel consists of discrete particles, or micelles, surrounded by solvated shells, and held together to form a semi-rigid structure by Van der Waal's forces. The chief of these forces is probably measured by the dipole moment. The addition of a peptizer causes partial or complete liquifaction of the gel by destroying the forces binding the micelles together. These forces, as well as the molecular weight of the micelles, would be statistical in nature. The weaker forces would be destroyed first, and this would result in a decrease in the average molecular weight of the micelles and consequently increased fluidity of the gel. Different materials have different peptizing power. It is conceivable that many of the peptizers would be capable of breaking the weaker of the forces acting between adjacent micelles and within the micelles themselves withoutweakening the stronger forces. These peptizers would result in only partial liquifaction of the gel, regardless of the amount of peptizer added. As the amount of peptizer is increased we would expect those properties that are fundamentally dependent on the intermicellar forces, such as viscosity, and Gardner consistency, would decrease rapidly at first and tend to reach a constant value.

The Gardner mobilometer slope versus percent xylenol is plotted in Figure (33). These curves, at low xylenol concentration, indicate that the slope is a straight line

FIGURE 33

XYLENOL PEPTIZED GELS

Gardner Slope vs % Xylenol



function of the xylenol content, but decreases to a constant value at higher concentration. In dealing with Gardner slopes for gels of this type, there is at least one factor affecting the slope. This factor is the change of viscosity with the rate of shear. If other variables are present, nothing certain can be said about them on the basis of Gardner Mobilometer data. Since the viscosity decreases with the addition of the peptizer to a minimum value (in some cases at least) we would expect an increase in Reynold's number and a decrease in friction factor. This should tend to increase the Gardner slope. The effect of peptizer on the rate of change of the viscosity with rate of change of rate of shear has not been investigated.

Figure (54) is the ST/VD relationship for the peptized gels. These curves too apparently tend to a definite maximum value.

8. Napalm Gels with Various Peptizers

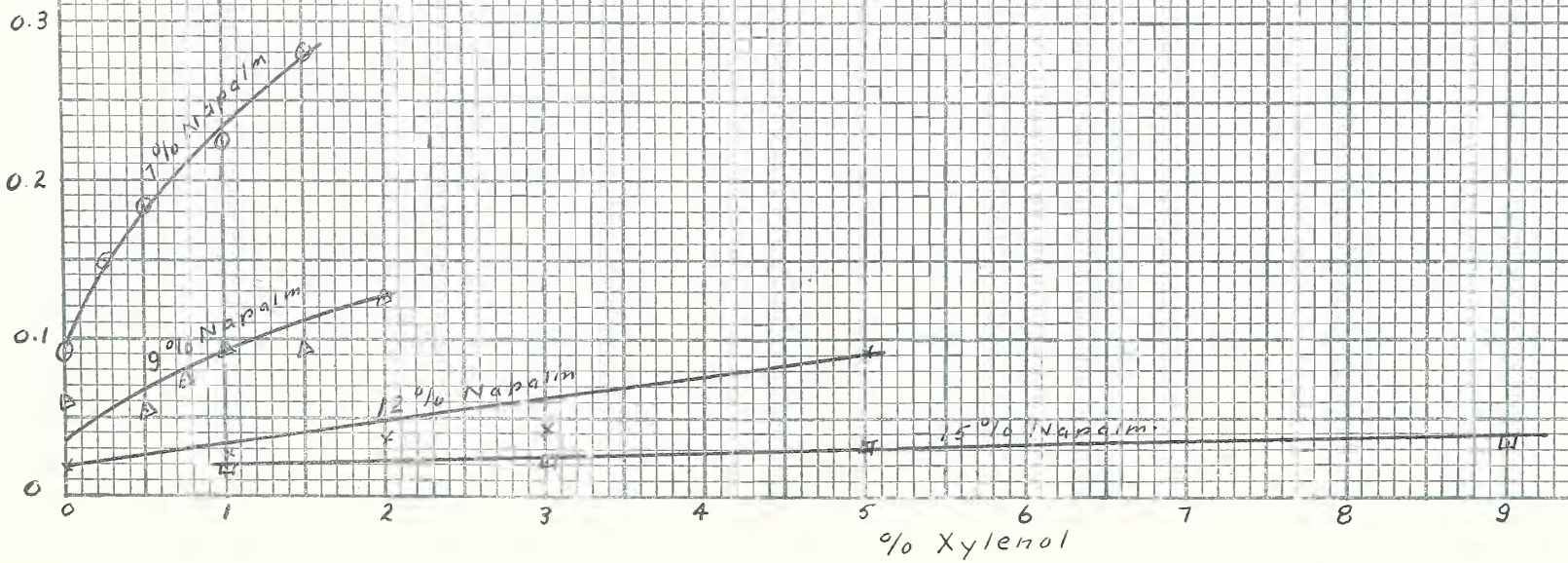
Figure (55) shows the correlation between range and ST/VD values obtained for napalm gels, the data for which are given in Table XII. The agreement here is not good in all instances. The gels containing tetralin, glycerol, benzaldehyde, β naphthol, xylenol, α naphthylamine, and aniline yield co-ordinates within the limit of experimental error; but gels containing water gives ranges about 15% low, 1.5% and .75% methanol - 30% low, and pyrogallol about 25% low.

A comparison of the gel containing tetralin with the straight napalm gel reveals the following:

FIGURE 34

XYLENOL PEPTIZED GELS

H.T./N.D vs % Xylenol



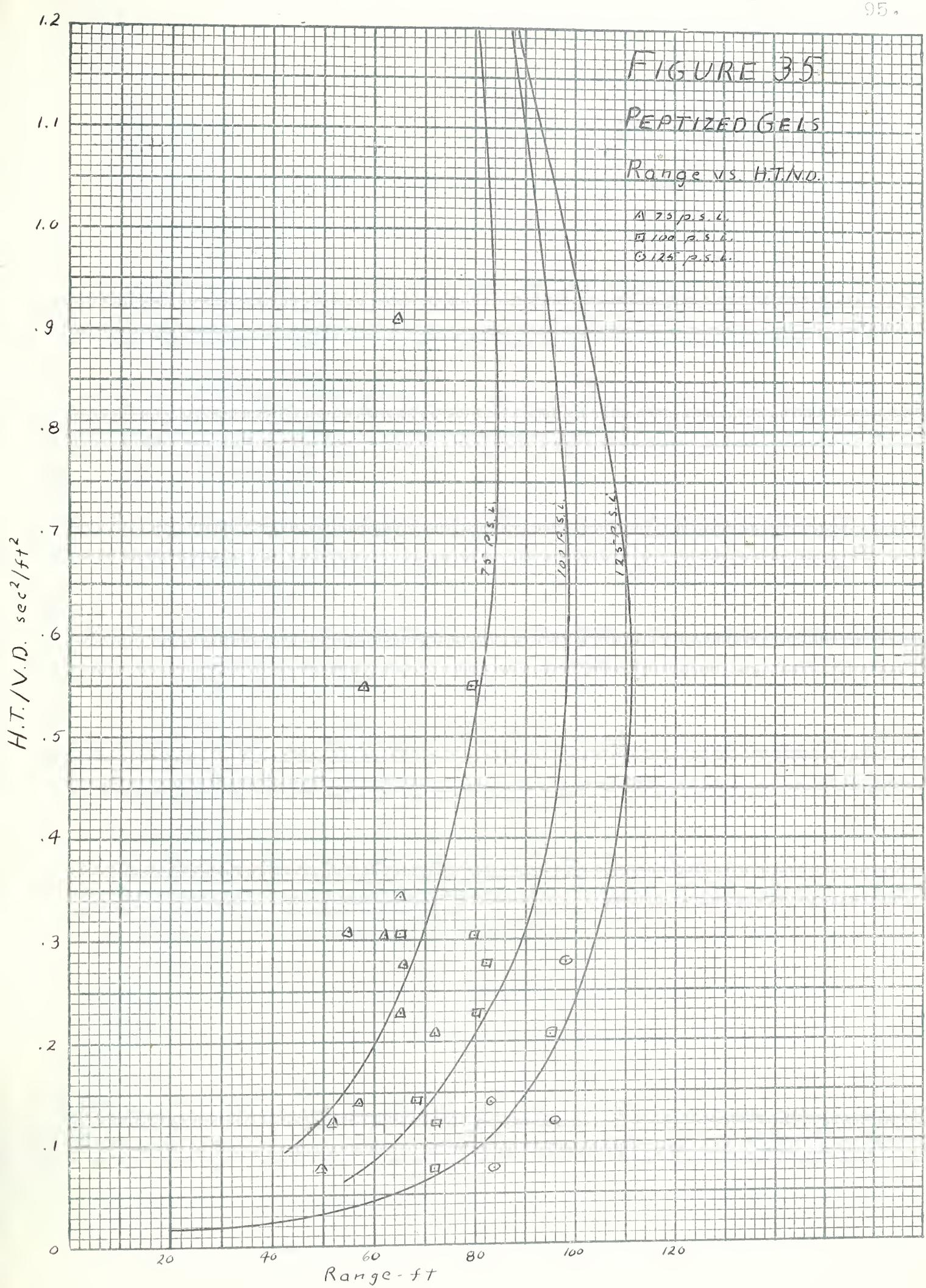


FIGURE 35
PEPTIZED GELS
Range vs. H.T./N.D.
△ 75 p.s.i.
□ 100 p.s.i.
○ 125 p.s.i.
75 p.s.i.
100 p.s.i.
125 p.s.i.
H.T./V.D. sec²/ft²
Range - ft
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
20
40
60
80
100
120

	Viscosity	130° Gardner	Gardner Slope	M/VD	Ranges 75	100	175
7% Napalm	8,940	[illegible]	0.27	0.093	43	63	85
7% Napalm, 1.5% tetralin	10,800	[illegible]	0.24	0.081	50	72	91

This reveals that tetralin did not act as a peptizer. This is in complete disagreement with the work of Knudsen and Bereda (20) who found that 1.5% tetralin resulted in complete breakdown of N.P.A.L. fuels after two days. The sample containing tetralin in this instance was five weeks old at the time of testing.

Of the other additives tested the peptizing action increased in the following order:

Benzaldehyde

Glycerol

α Naphthylamine

β Naphthol

Xylenol

Aniline

Water

Methanol

Pyrogallol

It is interesting to note that all the additives contain strongly polar groups, and all acted as peptizers. Tetralin does not contain a strongly polar group and its peptizing action is negligible or zero.

Of these, pyrogallol and methanol were extremely powerful, the Gardner slope indicating that there was little

change of viscosity with change of rate of shear, that is, their behavior approached that of Newtonian liquids. These Gardner slopes were approximately -0.75 which approaches -1 closely enough so that the difference may be accounted for by the minor changes in properties. In these two instances there may have been a chemical reaction between the Napalm and the pyrogallol or methanol. Both of the additives in higher concentrations resulted in the formation of a grey precipitate. In the case of lower concentrations, this precipitate may have been held in suspension by the gel since these were fairly viscous.

The water peptized gel had the appearance of an emulsion. If this were an emulsion of water in gasoline the Napalm would be acting as an emulsifier. This would change the physical properties of the gel. At low water concentrations the system would act as a gel but as the water content is increased, or the Napalm content decreased, the system would behave as an emulsion. This may possibly account for the Gardner consistency, etc., reaching a limiting minimum value at a water content of one quarter of the Napalm content.

Although glycerol contains three hydroxyl groups, it is inferior to methanol as a peptizer.

A comparison of the peptizing action of ∝naphthylamine and aniline reveals that on a weight basis aniline is the better peptizer. However, since ∝naphthylamine has a higher molecular weight, this is not an accurate basis for comparison; on an equi-molar basis this data indicates that

the peptizing power of these two amines would be approximately the same.

The peptizing action of xylenol and β naphthol were quite similar; on an equal weight basis the xylenol is slightly better. However, on an equi-molal basis these two would probably be nearly identical.

The above cases indicate that the extent of peptization is dependent on the nature of the polar group in the molecule, rather than on the dipole moment of the molecule as a whole.

A gel was prepared using 1.5% soap as a peptizer. This resulted in complete breakdown of the gel. This may have been due to the presence of impurities in the soap. However, a gel containing 1.5% C.P. sodium oleate behaved similarily.

SUMMARY

A piston driven pressure capillary viscosimeter has been designed which successfully overcomes the difficulty of channelling that is encountered in making viscosity and healing time measurements on thick gels using a gas driven pressure capillary viscosimeter. This apparatus has been used successfully as a model flame thrower to overcome this same difficulty which is encountered when direct gas pressure is used to eject the fuel.

Gardner Mobilometer measurements have been made on C.A.E. 60 oil at about -18°C.

Viscosity measurements at various rates of shear and Gardner Mobilometer measurements have been made on three gels. The composition of these gels were:

1. 8% Napalm
2. 12% Napalm, 2% Xylenol
3. 15% Napalm, 9% Xylenol

In cooperation with the staff of the Experimental Station at Suffield, Alberta, measurements of Gardner Mobilometer data, ball drop, healing time, and performance in a Wasp M.T. II flame thrower, were made on a series of eight straight Napalm gels varying from 3.25% to 7.5% Napalm.

Gardner Mobilometer data, initial viscosity by the ball drop method, healing time, and maximum range in a model flame thrower were obtained for straight 7, 9, and 12% Napalm gels, 7, 9, 12, and 15% Napalm gels containing various

amounts of xylenol, and 7% Napalm gels containing various additives.

The behaviour of the Gardner mobilometer seems analogous to that of a falling body rather than to that of flow through an orifice.

There is definite indication that "Gardner slope" is related to the rate of change of viscosity with rate of shear, but there is insufficient data to state precisely what this correlation is.

In studying straight Napalm gels the healing time was found to be a criterion for the prediction of field performance of a combat flame thrower operating under specific conditions. There is a definite relation between Gardner consistency and healing time, so that field performance is also related to Gardner consistency. Jet length is also related to healing time and independent of firing elevation; that is, jet length is dependent on the physical properties of the gel, whereas the behavior after jet breakup is dependent on the ballistics of the system.

The correlation between healing time and maximum range for straight Napalm gels is applicable to xylenol peptized gels and to gels containing other additives provided the nature of the gel is not destroyed. For peptized gels, however, neither Gardner consistency nor initial viscosity is a criterion for field performance.

The investigation of xylenol peptized gels indicate

that the effect of a peptizer increases as the proportion of peptizer is increased. A limiting value is reached for initial viscosity, Gardner slope, Gardner consistency, rolling time, etc. The minimum value for initial viscosity, etc., should be dependent on the Napalm concentration and to the peptizer and, in many cases, may well be too low to be of practical importance.

The peptizing action of an additive is dependent on the presence of a strongly polar group; the peptizing power of such an additive seems to be characterized by the polar group that it contains.

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